

DTIC

2

AD-A243 096



1991

PORT DOCUMENTATION PAGE

2a SECURITY CLASSIFICATION AUTHORITY		1b RESTRICTIVE MARKINGS	
2b DECLASSIFICATION / DOWNGRADING SCHEDULE		3 DISTRIBUTION / AVAILABILITY OF REPORT unlimited	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) 10		5 MONITORING ORGANIZATION REPORT NUMBER(S)	
6a NAME OF PERFORMING ORGANIZATION NIST	6b OFFICE SYMBOL (if applicable)	7a NAME OF MONITORING ORGANIZATION ONR	
6c ADDRESS (City, State, and ZIP Code) A329, Materials Building Gaithersburg, MD 20899-0001		7b ADDRESS (City, State, and ZIP Code) Code 1131 800 N. Quincy Street Arlington, VA 22217-5000	
8a NAME OF FUNDING / SPONSORING ORGANIZATION ONR	8b OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N0014-90-F-0011	
8c ADDRESS (City, State, and ZIP Code)		10 SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO	PROJECT NO
		TASK NO	WORK UNIT NO
11 TITLE (Include Security Classification) Transmission Electron Microscopy of the CVD Diamond Film/Substrate Interface			
12 PERSONAL AUTHOR(S) D. Shechtman			
13a. TYPE OF REPORT interim	13b. TIME COVERED FROM TO	14 DATE OF REPORT (Year, Month, Day) 91-9-27	15 PAGE COUNT 8
16 SUPPLEMENTARY NOTATION			
7 COSATI CODES		18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	
		This document has been approved for public release and sale: its distribution is unlimited.	
19 ABSTRACT (Continue on reverse if necessary and identify by block number)			
THIS PART OF THE STUDY CENTERED UPON THE DEFINITION OF THE CRYSTALLOGRAPHY OF TWINS IN CVD DIAMOND BY MEANS OF HIGH RESOLUTION ELECTRON MICROSCOPY. FOUR BASIC KINDS OF TWINS WERE STUDIED, NAMELY: FIRST, SECOND, THIRD AND FOURTH ORDER TWINS, DESIGNATED $\Sigma=3$, $\Sigma=9$, $\Sigma=27$ AND $\Sigma=81$ RESPECTIVELY. MOST OF THE $\Sigma=3$ TWINS ARE COHERENT BUT EXAMPLE IS GIVEN OF A NON COHERENT $\Sigma=3$ ONE. THE INTERACTION BETWEEN TWINS LEAD TO THE FORMATION OF HIGHER OR LOWER ORDER ONES AND A $\Sigma=81$ TWIN HAS BEEN OBSERVED TO REDUCE THE ENERGY OF THE BOUNDARY BY TRANSFORMING TO A $\Sigma=3$ TWIN. CONTRAST PHENOMENA RELATED TO TILTED TWINS WERE EXAMINED AND PREVIOUSLY UNSOLVED CONTRAST EXPLAINED. SEVERAL EXAMPLES OF TILTED $\Sigma=3$ AND $\Sigma=9$ TWINS ARE GIVEN. OTHER PHENOMENA RELATED TO THE CRYSTALLOGRAPHY OF TWIN QUINTUPLETS WILL BE REPORTED IN THE NEXT REPORT. IN THE FUTURE WE PLAN PLAN TO STUDY THE POSSIBILITY OF ANNEALING OUT VARIOUS TYPES OF TWIN BOUNDARIES IN DIAMOND FILMS.			
20 DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS		21 ABSTRACT SECURITY CLASSIFICATION unclassified	
22a NAME OF RESPONSIBLE INDIVIDUAL		22b TELEPHONE (Include Area Code)	22c OFFICE SYMBOL

OFFICE OF NAVAL RESEARCH

Contract N00014-90-F-0011

R&T Project No. IRMT 025

TECHNICAL REPORT No. 10

TRANSMISSION ELECTRON MICROSCOPY OF THE CVD
DIAMOND FILM/SUBSTRATE INTERFACE

by

D. Shechtman

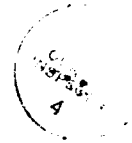
TECHNICAL REPORT TO SUBMITTED TO NIST

National Institute of Standards and Technology
Ceramics Division
Gaithersburg, MD 20899

and

Physics and Astronomy Department
The Johns Hopkins University
Baltimore MD

Accession For	
ADONIS	☒
ADONIS	☐
ADONIS	☐
Distribution	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or
	Special
A-1	



91-17312



September 27, 1991

Reproduction in whole or in part is permitted for
any purpose of the United States Government

This document has been approved for public release
and sale; its distribution is unlimited

01 1209 018

SUMMARY

THIS PART OF THE STUDY CENTERED UPON THE DEFINITION OF THE CRYSTALLOGRAPHY OF TWINS IN CVD DIAMOND BY MEANS OF HIGH RESOLUTION ELECTRON MICROSCOPY. FOUR BASIC KINDS OF TWINS WERE STUDIED, NAMELY: FIRST, SECOND, THIRD AND FOURTH ORDER TWINS, DESIGNATED $\Sigma=3$, $\Sigma=9$, $\Sigma=27$ AND $\Sigma=81$ RESPECTIVELY. MOST OF THE $\Sigma=3$ TWINS ARE COHERENT BUT EXAMPLE IS GIVEN OF A NON COHERENT $\Sigma=3$ ONE. THE INTERACTION BETWEEN TWINS LEAD TO THE FORMATION OF HIGHER OR LOWER ORDER ONES AND A $\Sigma=81$ TWIN HAS BEEN OBSERVED TO REDUCE THE ENERGY OF THE BOUNDARY BY TRANSFORMING TO A $\Sigma=3$ TWIN.

CONTRAST PHENOMENA RELATED TO TILTED TWINS WERE EXAMINED AND PREVIOUSLY UNSOLVED CONTRAST EXPLAINED. SEVERAL EXAMPLES OF TILTED $\Sigma=3$ AND $\Sigma=9$ TWINS ARE GIVEN. OTHER PHENOMENA RELATED TO THE CRYSTALLOGRAPHY OF TWIN QUINTUPLETS WILL BE REPORTED IN THE NEXT REPORT. IN THE FUTURE WE PLAN TO STUDY THE POSSIBILITY OF ANNEALING OUT VARIOUS TYPES OF TWIN BOUNDARIES IN DIAMOND FILMS.

INTRODUCTION

THE STRUCTURE OF GRAIN BOUNDARIES IN THE DIAMOND LATTICE, AND TWIN BOUNDARIES AS A SPECIAL CASE, RECEIVED CONSIDERABLE ATTENTION IN OVER THIRTY YEARS [1-14]. THIS IS MAINLY DUE TO THE IMPORTANCE OF DEFECTS IN SILICON AND GERMANIUM TO THEIR USEFULNESS AS EFFICIENT SEMICONDUCTORS. TWIN BOUNDARIES HAVE EQUAL IMPORTANCE TO VARIOUS PROPERTIES OF DIAMOND FILMS. ELECTRICAL AND MECHANICAL PROPERTIES AS WELL AS MIGRATION MECHANISMS ARE ALL AFFECTED BY THE TWIN BOUNDARIES AND THEIR STRUCTURE. THE EVER PRESENCE OF TWINS IN CVD DIAMOND FILMS MAKES THEIR STUDY EVEN MORE IMPORTANT COMPARED TO SEMICONDUCTORS WHICH CAN BE GROWN WITHOUT BOUNDARIES.

THE PURPOSE OF THE STUDY REPORTED HERE IS, THEREFORE, TO INVESTIGATE THE CRYSTALLOGRAPHY OF TWIN BOUNDARIES WHICH FORM IN CHEMICAL VAPOR DEPOSITED (CVD) DIAMOND FILMS, AND TO COMPARE THEM TO THE ONES WHICH WERE FOUND IN SILICON AND IN GERMANIUM. HIGH RESOLUTION ELECTRON MICROSCOPY, WHICH WAS USED IN THIS STUDY, RESOLVED THE FINE STRUCTURE OF TWIN BOUNDARIES AND THE RESULTS PRESENT A VIEW OF THE TYPE OF TWINS PRESENT IN DIAMOND THIN FILMS. OUR OBSERVATIONS INCLUDE TWIN BOUNDARIES WHICH WERE NEVER REPORTED BEFORE IN DIAMOND LATTICE MATERIALS.

TWIN BOUNDARIES IN THE DIAMOND LATTICE

TWIN BOUNDARIES CAN BE SPECIFIED BY A ROTATION AXIS, AROUND WHICH THE TWINS ARE ROTATED RELATIVE TO ONE ANOTHER, BY A ROTATION ANGLE, THE TWINNING PLANE K_1 AND BY THE PARAMETER Σ DEFINED AS THE RECIPROCAL OF THE DENSITY OF COINCIDENT SITES OF THE OVERLAPPING LATTICES ON BOTH SIDES OF THE BOUNDARY. THE TYPE OF BOUNDARIES REPORTED HERE INCLUDE $\Sigma=3$, $\Sigma=9$, $\Sigma=27$ AND $\Sigma=81$.

THE ROTATION AXIS

THE ROTATION AXIS OF ALL THE TWINS REPORTED HERE IS $\langle 110 \rangle$. THE HIGH RESOLUTION ELECTRON MICROSCOPY MICROGRAPHS WHICH WILL BE SHOWN HAVE ALL A WELL ALIGNED $\langle 110 \rangle$ ZONE AXIS AND THE STUDIED TWINS ARE, THEREFORE, VIEWED EDGE-ON. THIS CONFIGURATION ALLOWS FOR A DETAILED AND RELATIVELY SIMPLE STUDY OF THE TWIN BOUNDARY'S STRUCTURAL DETAILS.

THE ROTATION ANGLE

THE ROTATION ANGLES OF DIAMOND TWINS CAN BE DETERMINED AS FOLLOWS:

FOR $\Sigma=3$ ORIENTATION RELATIONSHIP $\phi = 2\text{tg}^{-1} \sqrt{2}/2 = 70.52877936^\circ$

FOR $\Sigma=9$ ORIENTATION RELATIONSHIP $\alpha = 180 - 2[2\text{tg}^{-1} \sqrt{2}/2] = 38.94244128^\circ$

FOR $\Sigma=27$ ORIENTATION RELATIONSHIP $\alpha = -180 + 3[2\text{tg}^{-1} \sqrt{2}/2] = 31.58633808^\circ$

FOR $\Sigma=81$ ORIENTATION RELATIONSHIP $\alpha = 360 - 4[2\text{tg}^{-1} \sqrt{2}/2] = 77.88488256^\circ$

THE MISMATCH ANGLE IN A TWIN QUINTUPLET $\alpha = 360 - 5[2\text{tg}^{-1} \sqrt{2}/2] = 7.35610319^\circ$

DEFINITIONS:

1. **COHERENT TWIN** - CONTAINS CORRESPONDING LATTICE PLANES AND DIRECTIONS WHICH ARE CONTINUOUS ACROSS THE TWINNING PLANE. MOST OF THE $\Sigma=3$ TWINS THAT WE HAVE STUDIED WERE COHERENT. THERE WERE SEVERAL EXCEPTIONS IN WHICH WE OBSERVED INCOHERENT BOUNDARIES.

2. **INCOHERENT TWIN** (ALSO CALLED LATERAL TWIN, SEMICOHERENT, NONCOHERENT OR INCOHERENT TWIN) - IS THE CASE IN WHICH THE TWIN PLANE AND THE BOUNDARY PLANE ARE NOT COINCIDENT.

3. **THE ORDER OF A TWIN BOUNDARY** - A FIRST ORDER TWIN BOUNDARY RESULTS FROM ONE OF THE TWINNING OPERATIONS, FOR EXAMPLE: A $\{111\}$ $\Sigma=3$ BOUNDARY WHICH RESULTS FROM A 70.53° ROTATION AROUND THE $\langle 110 \rangle$ AXIS. A SECOND ORDER TWIN BOUNDARY WILL FORM WHEN A TWINNING OPERATION IS PERFORMED IN A CRYSTAL DIVIDING IT, FOR EXAMPLE TO TWIN [A] AND TWIN [B]. IF TWIN [B] WILL TWIN AGAIN TO CREATE TWIN [C], AND THIS ONE WILL BE IN CONTACT WITH TWIN [A], THE BOUNDARY BETWEEN THEM IS A SECOND ORDER TWIN BOUNDARY, $\Sigma=9$. A THIRD ORDER TWIN BOUNDARY, $\Sigma=27$ FORMS SIMILARLY WHEN TWIN [C] TWINS AND THE RESULTANT TWIN [D] IS IN CONTACT WITH TWIN [A]. A FORTH ORDER TWIN BOUNDARY, FORMS AFTER FOUR STAGES OF TWINNING. KOHN [10] SUGGESTED THAT THIS TYPE OF TWIN BOUNDARY IS MUCH LIKE A HIGH ENERGY COMMON GRAIN BOUNDARY.

RESULTS

AN EXAMPLE IN WHICH FOUR KINDS OF TWINS INTERACT IS GIVEN IN FIGURE 1 [203-3]. AS IT CAN BE CLEARLY SEEN, THE CRYSTAL IS DIVIDED INTO TWO. THE UPPER PORTION HAS TWO ORIENTATIONS, DENOTED 1A AND 1B WHILE THE LOWER PORTION IS DIVIDED INTO FOUR ORIENTATIONS DENOTED 2A, 2B, 2C AND 2D. WHILE IN EACH PORTION MOST OF THE TWIN BOUNDARIES ARE OF THE $\Sigma=3$ TYPE, EXCEPT FOR THE AREA AROUND THE 2D ORIENTATION, THE BOUNDARY THAT DIVIDES THE TWO PORTIONS IS OF A HIGHER ORDER. IN ORDER TO SHOW THE SIGNIFICANT POINTS ALONG THIS BOUNDARY WE HAVE MARKED BY LETTERS THE POINT OF INTERSECTION BETWEEN IT AND THE VARIOUS $\Sigma=3$ BOUNDARIES. ALSO MARKED ARE THE $\{111\}$ PLANES IN THE VARIOUS TWINS.

BETWEEN POINT A AND POINT B, A $\Sigma=9$ BOUNDARY CAN BE SEEN, EXCLUDING BRIEF ENCOUNTERS AT POINTS A' AND A" WITH $\Sigma=3$ BOUNDARIES WHICH FORM VERY NARROW TWINS. THIS BOUNDARY HAS A MISORIENTATION ANGLE OF 38.94° ABOUT $[110]$. AT POINT A THE BOUNDARY INTERACTS WITH A $\Sigma=3$ BOUNDARY TO FORM A $\Sigma=27$ BOUNDARY WITH A MISORIENTATION ANGLE OF 31.59° ABOUT $[110]$. ON THE LEFT HAND SIDE, AT POINT B, THE $\Sigma=9$ BOUNDARY INTERACTS WITH TWO $\Sigma=3$ BOUNDARIES TO FORM A $\Sigma=81$ BOUNDARY WITH A MISORIENTATION ANGLE OF 77.88° . THIS FORTH ORDER BOUNDARY STRETCHES BETWEEN POINTS B AND C AND ONE OF ITS CHARACTERISTICS IS THE MISMATCH ANGLE OF 7.36° BETWEEN THE $\{111\}$ PLANES ON BOTH SIDES OF THE BOUNDARY. THIS IS CLEARLY OBSERVED ALSO BETWEEN THE INCOHERENT TWINS OF A TWIN QUINTUPLET [SEE REPORT #4, 1990]. IN THE PRESENT CASE THE MISMATCH ANGLE CLOSES AT POINT C TO FORM A LOW ENERGY $\Sigma=3$ BOUNDARY.

ANOTHER POINT THAT SHOULD BE NOTED HAS TO DO WITH THE COHERENCY OF THE $\Sigma=3$ BOUNDARIES. USUALLY THESE BOUNDARIES ARE ON THE COMMON (111) PLANE AND ARE THEREFORE COHERENT BOUNDARIES. THE $\Sigma=3$ BOUNDARIES SHOWN HERE ARE NO EXCEPTION. HOWEVER, IN ONE CASE, SEEN AT THE LOWER RIGHT PART, THE $\Sigma=3$ TWIN TILTS FROM THE COMMON (111) PLANE TO THE OTHER EDGE-ON (111) PLANE OF THE 2a ORIENTATION. THIS IS A RARE CASE, IN GENERAL, AND THE ONLY ONE IN THIS MICROGRAPH.

INCLINED TWINS

ALL THE TWIN BOUNDARIES SHOWN IN FIGURE 1 ARE ESSENTIALLY EDGE-ON, PRESENT NO CONTRAST PROBLEMS AND ENABLE AN EXAMINATION OF THE BOUNDARIES' FINE STRUCTURE. IN OTHER PARTS THE TWIN BOUNDARIES ARE FOUND TO BE IN A NON EDGE-ON POSITION WHICH RESULTS IN A CONTRAST EFFECT THAT CAN NOT BE RELATED DIRECTLY TO THE FINE STRUCTURE OF THE BOUNDARY. AN EXAMPLE OF SUCH A CASE IS GIVEN IN FIGURE 2 [202-2].

IN THIS EXAMPLE, THE UPPER PORTION OF THE MICROGRAPH HAS AN ORIENTATION DENOTED AS 1a WHILE THE LOWER PORTION IS TWINNED BETWEEN THE 2a AND 2b ORIENTATIONS AS MARKED. THE BOUNDARY THAT SEPARATES THE UPPER PORTION FROM THE LOWER ONE IS NOT EDGE-ON AND CAN BE DIVIDED INTO SECTIONS OF $\angle=3$ AND $\angle=9$ ACCORDING TO THE THE ORIENTATIONS BETWEEN 1a-2a AND 1a-2b. THE CONTRAST OBSERVED, OF THE TILTED $\angle=3$ AND $\angle=9$ IS RATHER TYPICAL, AND IT HAS BEEN OBSERVED, WITH MINOR CHANGES, AND RECORDED MANY TIMES DURING THE COURSE OF THIS STUDY. IT IS DIFFICULT TO ESTIMATE THE INCLINATION ANGLE FOR EACH BOUNDARY AT THIS POINT, BUT LATTICE SIMULATION EXPERIMENT SHOULD BE ABLE TO DEFINE IT BETTER.

BIBLIOGRAPHY

SILICON

1. M.D. VAUDIN, B. CUNNINGHAM AND D.G. AST, SCRIPTA MET. 17, 191 (1983).
2. B. CUNNINGHAM, H.P. STRUNK AND D.G. AST, SCRIPTA MET., 16, 349 (1982).
3. C. FONTAIN AND D.A. SMITH, APPL. PHYS. LETT. 40, 153 (1982).
4. Z. ELGAT AND C.B. CARTER, ULTRAMICROSCOPY 18, 313 (1985).
5. C. D'ANTRERROCHES AND A. BOURRET, PHIL. MAG., 49, 783 (1984).
6. J. HONSTRA, PHYSICA 25, 409 (1959).
7. V.A. PHILLIPS, ACTA MET. 20, 1143 (1972).
8. H.-J. MOLLER, PHIL. MAG. A, 43, 1045 (1981).
9. R.C. POND, J. DE PHISIQUE 43, C1-51 (1982).
10. J.A. KOHN, THE AMERICAN MINEROLOGIST 43, 263 (1958).

DIAMOND

11. B.E. WILLIAMS, H.S. KONG AND J.T. GLASS, J. MATER. RES., 5, 801 (1989).
12. B.E. WILLIAMS AND J.T. GLASS, J. MATER. RES., 4, 373 (1989).
13. J. NARAYAN AND A.R. SRIVASTA, APPL. PHYS. LETT. 53, 1823 (1988).
14. J. NARAYAN, J. MATER. RES. 5, 2414 (1990).

Figure 1

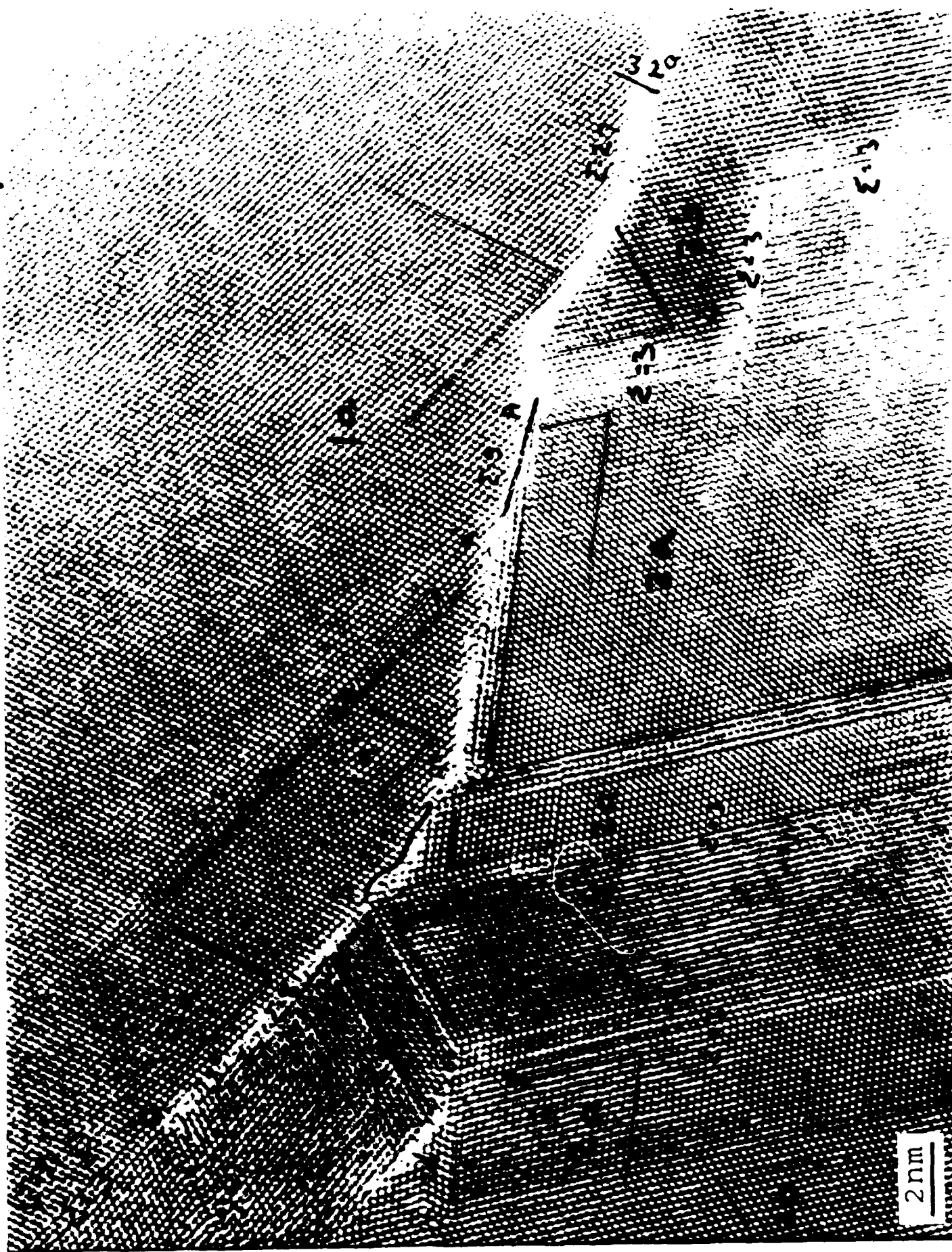


figure 2



6 March 1991

FY91 ONR DOMES ARI CONTRACTORS

Dr. Duncan W. Brown
Advanced Technology Materials, Inc.
520-B Danbury Road
New Milford, CT 06776
(203) 355-2681

Dr. Mark A. Cappelli
Stanford University
Mechanical Engineering Dept.
Stanford, CA 94305
(415) 723-1745

Dr. R. P. H. Chang
Materials Science & Engineering Dept.
2145 Sheridan Road
Evanston, IL 60208
(312) 491-3598

Dr. Bruce Dunn
UCLA
Chemistry Department
Los Angeles, CA 90024
(213) 825-1519

Dr. Al Feldman
Leader, Optical Materials Group
Ceramics Division
Materials Science & Engineering Lab
NIST
Gaithersburg, MD 20899
(301) 975-5740

Dr. John Field
Department of Physics
University of Cambridge
Cavendish Laboratory
Madingley Road
Cambridge CB3 0HE
England
44-223-337733, ext. 7318

Dr. William A. Goddard, III
Director, Materials and Molecular
Simulation Center
Beckman Institute
California Institute of Technology
Pasadena, CA 91125
(818) 356-6544
Fax: (818) 568-8824

Dr. David Goodwin
California Institute of Technology
Mechanical Engineering Dept.
Pasadena, CA 91125
(818) 356-4249

Dr. Alan Harker
Rockwell Int'l Science Center
1049 Camino Dos Rios
P.O. Box 1085
Thousand Oaks, CA 91360
(805) 373-4131

Mr. Stephen J. Harris
General Motors Research Laboratories
Physical Chemistry Department
30500 Mound Road
Warren, MI 48090-9055
(313) 986-1305
Fax: (313) 986-8697
E-mail: sharris@gmr.com

Dr. Rudolph A. Heinecke
Standard Telecommunication
Laboratories, Ltd.
London Road
Harlow, Essex CM17 9MA
England
44-279-29531, ext. 2284

Dr. Kelvin Higa
Code 3854
Naval Weapons Center
China Lake, CA 93555-6001

Enclosure (1)

Dr. Curt E. Johnson
Code 3854
Naval Weapons Center
China Lake, CA 93555-6001
(619) 939-1631

Dr. J. J. Mecholsky, Jr.
University of Florida
Materials Science & Engineering Dept.
256 Rhines Hall
Gainesville, FL 32611
(904) 392-1454

Dr. Rishi Raj
Cornell University
Materials Science & Engineering Dept.
Ithaca, NY 14853
(607) 255-4040

Dr. Rustum Roy
Pennsylvania State University
Materials Research Laboratory
University Park, PA 16802
(814) 865-2262

Dr. James A. Savage
Royal Signals & Radar Establishment
St. Andrews Road
Great Malvern, Worcs WR14.3PS
England
01-44-684-895043

Dr. Y. T. Tzeng
Auburn University
Electrical Engineering Dept.
Auburn, AL 36849
(205) 884-1869

Dr. Terrell A. Vanderah
Code 3854
Naval Weapons Center
China Lake, CA 93555-6001
(619) 939-1654

Dr. George Walrafen
Howard University
Chemistry Department
525 College Street N.W.
Washington, D.C. 20059
(202) 636-6897/6564

Dr. Aaron Wold
Brown University
Chemistry Department
Providence, RI 02912
(401) 863-2857

Dr. Wally Yarborough
Pennsylvania State University
Materials Research Laboratory
University Park, PA 16802
(814) 865-7102

6 March 1991

DISTRIBUTION LIST

Mr. James Arendt
Hughes Aircraft Company
8433 Fallbrook Ave. 270/072
Canoga Park, CA 91304
(838) 702-2890

Mr. Larry Blow
General Dynamics
1525 Wilson Blvd., Suite 1200
Arlington, VA 22209
(703) 284-9107

Mr. Ellis Boudreaux
Code AGA
Air Force Armament Laboratory
Eglin AFB, FL 32542

Dr. Duncan W. Brown
Advanced Technology Materials, Inc.
520-B Danbury Road
New Milford, CT 06776
(203) 355-2681

Dr. Mark A. Cappelli
Stanford University
Mechanical Engineering Dept.
Stanford, CA 94305
(415) 723-1745

Dr. R. P. H. Chang
Materials Science & Engineering Dept.
2145 Sheridan Road
Evanston, IL 60208
(312) 491-3598

Defense Documentation Center
Cameron Station
Alexandria, VA 22314
(12 copies)

Dr. Al Feldman
Leader, Optical Materials Group
Ceramics Division
Materials Science & Engineering Lab
NIST
Gaithersburg, MD 20899
(301) 975-5740

Dr. John Field
Department of Physics
University of Cambridge
Cavendish Laboratory
Madingley Road
Cambridge CB3 0HE
England
44-223-337733, ext. 7318

Dr. William A. Goddard, III
Director, Materials and Molecular
Simulation Center
Beckman Institute
California Institute of Technology
Pasadena, CA 91125
(818) 356-6544
Fax: (818) 568-8824

Dr. David Goodwin
California Institute of Technology
Mechanical Engineering Dept.
Pasadena, CA 91125
(818) 356-4249

Dr. Kevin Gray
Norton Company
Goddard Road
Northboro, MA 01532
(508) 393-5968

Mr. Gordon Griffith
WRDC/MLPL
Wright-Patterson AFB, OH 45433

Dr. H. Guard
Office of Chief of Naval Research
(ONR Code 1113PO)
800 North Quincy Street
Arlington, VA 22217-5000

Dr. Alan Harker
Rockwell Int'l Science Center
1049 Camino Dos Rios
P.O. Box 1085
Thousand Oaks, CA 91360
(805) 373-4131

Enclosure (2)

Mr. Stephen J. Harris
General Motors Research Laboratories
Physical Chemistry Department
30500 Mound Road
Warren, MI 48090-9055
(313) 986-1305
Fax: (313) 986-8697
E-mail: sharris@gmr.com

Dr. Rudolph A. Heinecke
Standard Telecommunication
Laboratories, Ltd.
London Road
Harlow, Essex CM17 9MA
England
44-279-29531, ext. 2284

Dr. Curt E. Johnson
Code 3854
Naval Weapons Center
China Lake, CA 93555-6001
(619) 939-1631

Dr. Larry Kabacoff (Code R32)
Officer in Charge
Naval Surface Weapons Center
White Oak Laboratory
10901 New Hampshire
Silver Spring, MD 20903-5000

Mr. M. Kinna
Office of Chief of Naval Research
(ONT Code 225)
800 North Quincy Street
Arlington, VA 22217-5000

Dr. Paul Klocek
Texas Instruments
Manager, Advanced Optical Materials Branch
13531 North Central Expressway
P.O. Box 655012, MS 72
Dallas, Texas 75268
(214) 995-6865

Ms. Carol R. Lewis
Jet Propulsion Laboratory
4800 Oak Grove Drive
Mail Stop 303-308
Pasadena, CA 91109
(818) 354-3767

Dr. J. J. Mecholsky, Jr.
University of Florida
Materials Science & Engineering Dept.
256 Rhines Hall
Gainesville, FL 32611
(904) 392-1454

Dr. Russ Messier
Pennsylvania State University
Materials Research Laboratory
University Park, PA 16802
(814) 865-2262

Mr. Mark Moran
Code 3817
Naval Weapons Center
China Lake, CA 93555-6001

Mr. Ignacio Perez
Code 6063
Naval Air Development Center
Warminster, PA 18974
(215) 441-1681

Mr. C. Dale Perry
U.S. Army Missile Command
AMSMI-RD-ST-CM
Redstone Arsenal, AL 35898-5247

Mr. Bill Phillips
Crystallume
125 Constitution Drive
Menlo Park, CA 94025
(415) 324-9681

Dr. Rishi Raj
Cornell University
Materials Science & Engineering Dept.
Ithaca, NY 14853
(607) 255-4040

Dr. M. Ross
Office of Chief of Naval Research
(ONR Code 1113)
800 North Quincy Street
Arlington, VA 22217-5000

Dr. Rustum Roy
Pennsylvania State University
Materials Research Laboratory
University Park, PA 16802
(814) 865-2262

Dr. James A. Savage
Royal Signals & Radar Establishment
St. Andrews Road
Great Malvern, Worcs WR14.3PS
England
01-44-684-895043

Mr. David Siegel
Office of Chief of Naval Research
(ONT Code 213)
800 North Quincy Street
Arlington, VA 22217-5000

Dr. Keith Snail
Code 6520
Naval Research Laboratory
Washington, D.C. 20375
(202) 767-0390

Dr. Y. T. Tzeng
Auburn University
Electrical Engineering Dept.
Auburn, AL 36849
(205) 884-1869

Dr. George Walrafen
Howard University
Chemistry Department
525 College Street N.W.
Washington, D.C. 20054
(202) 806-6897/6564

Mr. Roger W. Whatmore
Plessey Research Caswell Ltd.
Towcester Northampton NN128EQ
England
(0327) 54760

Dr. Charles Willingham
Raytheon Company
Research Division
131 Spring Street
Lexington, MA 02173
(617) 860-3061

Dr. Robert E. Witkowski
Westinghouse Electric Corporation
1310 Beulah Road
Pittsburgh, PA 15235
(412) 256-1173

Dr. Aaron Wold
Brown University
Chemistry Department
Providence, RI 02912
(401) 863-2857

Mr. M. Yoder
Office of Chief of Naval Research
(ONR Code 1114SS)
800 North Quincy Street
Arlington, VA 22217-5000