

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED FINAL 1/01/92 - 12/31/94
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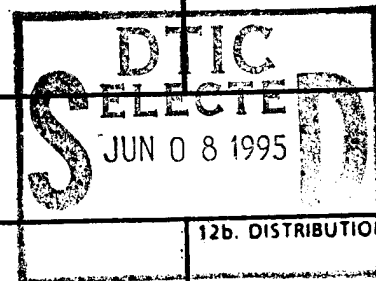
4. TITLE AND SUBTITLE DEVELOPMENT OF THIN FILM DIAMOND BASED INTEGRATED CIRCUIT TECHNOLOGY	5. FUNDING NUMBERS N000014-92-J-1421
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) THE PENNSYLVANIA STATE UNIVERSITY UNIVERSITY PARK, PA 16802	8. PERFORMING ORGANIZATION REPORT NUMBER 80.1
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) OFFICE OF NAVAL RESEARCH MAX N. YODER CODE 312 ROOM #607, 800 N. QUINCY STREET ARLINGTON, VA 22217-5660	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
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11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION/AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED	12b. DISTRIBUTION CODE
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13. ABSTRACT (Maximum 200 words)

IN THE PORTION OF THIS PROJECT FUNDED BY BMDO/IST, WE HAVE BEEN DEVELOPING THE ELEMENTS OF A DIAMOND BASED SEMICONDUCTOR TECHNOLOGY FOR HIGH TEMPERATURE APPLICATIONS. THE APPROACH IS CENTERED AROUND INCORPORATING A SCHOTTKY BARRIER CONTACT AND MOS FIELD-EFFECT TRANSISTOR USING DIAMOND FILMS PREPARED BY MICROWAVE PLASMA CHEMICAL VAPOR DEPOSITION (MPACVD). THE EXPERIMENTAL BASIS FOR THIS RESEARCH IS THE SUCCESSFUL FABRICATION IN OUR LABORATORY OF THE WORLD'S FIRST SCHOTTKY DIODES WITH PACVD DIAMOND BASE. THESE DEVICES HAVE CHARACTERISTICS SIMILAR TO THEIR COUNTERPARTS FABRICATED USING SINGLE CRYSTAL SYNTHETIC DIAMOND PREPARED BY HIGH PRESSURE METHODS. THIS HAS REQUIRED A DETAILED UNDERSTANDING AND CONTROL OF THE DEPOSITION PROCESS AS IT RELATES TO THE CHEMICAL PURITY AND STRUCTURAL PERFECTION OF THE RESULTING SINGLE CRYSTAL DIAMOND FILMS. IN ADDITION, DETAILED CHARACTERIZATION OF THE FILMS HAS ALLOWED FOR MEANINGFUL PREPARATION-CHARACTERIZATION-ELECTRONIC PROPERTY RELATIONS. THE ULTIMATE GOAL OF THE PROPOSED RESEARCH IS TO FABRICATE TRANSISTORS ON SINGLE CRYSTAL HETEROEPITAXIAL DIAMOND AND TO FABRICATE SMALL SCALE INTEGRATED CIRCUIT OPERATIONAL AT 400-500°C.

DTIC QUALITY INSPECTED 3

14. SUBJECT TERMS DIAMOND ELECTRONICS MICROWAVE PLASMA CHEMICAL VAPOR DEPOSITION HIGH TEMPERATURE SCHOTTKY DIODE, FIELD-EFFECT TRANSISTOR	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
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19950605 047

PUBLICATIONS  
Grant #N000014-92-J-1421

A. Badzian and T. Badzian, "Routes to Diamond Homoepitaxy" Mat. Res. Soc. Symp. Proc. Chemical Vapor Deposition of Refractory Metals and Ceramics II, ed. T.M. Besmann, B.M. Gallois, J.W. Warren, Mat. Res. Soc. Pittsburgh, PA, Vol.250, 339-349, 1992

S.A. Grot, R.A. Ditzio, G.Sh. Gildenblat, A.R. Badzian, and S.J. Fonash "Electronic Device Fabrication Using Electron Cyclotron Resonance Etching of Boron Doped Homoepitaxial Diamond Films", Mat. Res. Symp. Proc. Vol. 242, pp.145-150, 1992

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G.P. Lamaze, R.G. Downing, L. Pilione, A.Badzian, and T. Badzian "Analysis of Boron in CVD Diamond Surfaces Using Neutron Depth Profiling" 6-th International Conference on Solid Films and Surfaces, Paris, France, June 29-July 3, 1992, Applied Surface Science, 65/66, 587-592, 1993

S. A. Grot, R.A. Ditzio, G.Sh. Gildenblat, A.R. Badzian, and S.J. Fonash "Oxygen Based Electron Cyclotron Resonance Etching of Semiconducting Homoepitaxial Diamond Films" Applied Physics Letters 61, 2326-2328, 1992

A. Badzian and T. Badzian "Diamond Homoepitaxy by Chemical Vapor Depositions", Diamond and Related Materials, 2, pp.147-157, 1993

B. Yacobi, J. Lebens and K.J. Vahala, A. Badzian, and T. Badzian " Preferential Incorporation of Defects in Monocrystalline Diamond Films", Diamond and Related Materials , 2, 92-99, 1993

Y.-J. Baik, K.Y. Eun, and A. Badzian "Effect of Growth Plane Index of Polycrystalline Diamond Film on Raman Spectrum " ADC '93 2nd International Conference on the Applications of Diamond Films and Related Materials, Omiya, Saitama, Japan, August 25-27, 1993, MYU, Tokyo, Japan , 709-714, 1993

A. Badzian, T.Badzian and S.-Tong Lee "Synthesis of Diamond from Methane and Nitrogen Mixture", ed. J.P. Dismukes and K.V. Ravi, Diamond Materials. The Electrochemical Society, Inc., Pennington, NJ, 378-384 , 1993

A. Badzian and T.Badzian "High Temperature Epitaxy of Diamond", ed. J.P. Dismukes and K.V. Ravi, Diamond Materials. The Electrochemical Society, Inc., Pennington, NJ, 1060-1066, 1993

A. Badzian and T. Badzian "Nickel Hydride Assistance in CVD Diamond Growth", ed. J.P. Dismukes and K.V. Ravi , Diamond Materials. The Electrochemical Society, Inc., Pennington NJ, 441, 1993

A. Badzian, T. Badzian and S. Tong Lee "Synthesis of Diamond from Methane and Nitrogen Mixture", Appl. Phys. Lett., 62, 3432-3434 (1993)

A. Badzian and T. Badzian "Crystal Growth of Diamond and Nickel Carbide in the Ni-C-H System", ed. M. Kamo, H. Kanda, Y. Matsui and T. Sekine, Advanced Materials. International Communications Specialists, Inc. 140-145, 1994

A. Badzian and T. Badzian " Defects in CVD Diamonds" Proceedings of the 8th CIMTEC - World Ceramic Congress and Forum on New Materials, Florence, Italy June 29-July 4, 94  
/in press/

G.P. Lamaze, A. Badzian, T. Badzian, R.G. Downing, and L. Pione "Boron and Nitrogen Analysis in CVD Diamond Films Using Cold Neutron Depth Profiling " ed. M.Yoshikawa et al, Advances in New Diamond Science and Technology, Fourth Internatinal Conference on the New Diamond Science and Technology, 341-344, 1994

N. Lee and A. Badzian "Effect of misorientation angles on the surface morfologies of (001) homoepitaxial diamond thin films" Applied Physics Letters, 66, 2203-2205, 1995

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Unannounced	<input type="checkbox"/>
Justification .....	
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**PRESENTATIONS**  
Grant #N000014-92-J-1421

A. Badzian and T. Badzian "Interfaces in Diamond Nucleation Processes" International Conference on Metallurgical Coatings and Thin Films, April 6-10, 1992, San Diego, CA (symposium chairman)

A. Badzian "Overview of CVD Diamond Deposition" American Vacuum Society New England Chapter, 1992 Annual Symposium - May 18-19, 1992 Burlington, Ma. (invited talk)

A. Badzian and T. Badzian "Heteroepitaxy of Diamond on Cubic Boron Nitride" Gordon Research Conference, Diamond Synthesis, June 15-19, 1992, Plymouth, NH (poster presentation)

G.P. Lamaze, R.G. Downing, L. Pilione, A. Badzian and T. Badzian "Analysis of Boron in CVD Diamond Surfaces Using Neutron Depth Profiling" 6-th International Conference on Solid Films and Surfaces, Paris France, June 29 - July 3, 1992

A. Badzian and T. Badzian "Diamond Homoepitaxy" Third International Conference on the New Diamond Science and Technology, Heidelberg, Germany, August 31 - September 4, 1992 /oral presentation, cBN session chairman /

B.G. Yacobi, J. Lebens, K.J. Vahala, A.R. Badzian, and T. Badzian "Preferential Incorporation of Defects in Monocrystalline Diamond Films" Third International Conference on the New Diamond Science and Technology, Heidelberg, Germany, August 31 - September 4, 1992

G.Sh. Gildenblat, S.A. Grot, A.R. Badzian "Diamond Electronic Devices - State of Art" Third International Conference on the New Diamond Science and Technology, Heidelberg, Germany, August 31 - September 4, 1992 /invited talk/

A. Badzian "Issues on Diamond Synthesis, Crystal Structure and Properties" invited talk at Nishi Tokyo University, Tokyo, Japan, December 1992

A. Badzian "Synthesis and Crystal Structure of Boron - Carbon - Nitrogen Phases" invited talk at National Institute in Research in Inorganic Materials, Tsukuba, Japan, December 1992

A. Badzian and T. Badzian "High Temperature Limit for CVD Diamond Growth" International Conference on Metallurgical Coatings and Thin Films, San Diego, CA, April 19-23, 1993

A. Badzian "Progress Report on Project: Transistor on Heteroepitaxial Diamond" Combined DARPA / SDIO / ONR Diamond Program Review, Arlington, Virginia, 27-30 April, 1993

A. Badzian, T. Badzian and S.-Tong Lee "Synthesis of Diamond from Methane and Nitrogen Mixture" 183rd Meeting of the Electrochemical Society, Honolulu, Hawaii, May 16-21, 1993

A. Badzian and T. Badzian "High Temperature Epitaxy of Diamond" 183rd Meeting of the Electrochemical Society, Honolulu, Hawaii, May 16-21, 1993

A. Badzian and T. Badzian "Nickel Hydride Assistance in CVD Diamond Growth" 183rd Meeting

of the Electrochemical Society, Honolulu, Hawaii, May 16-21, 1993

R. Roy and A. Badzian "Nontraditional Approaches to Diamond Synthesis" The 3rd IUMRS (International Union of Materials Research Societies) International Conference on Advanced Materials, Sunshine City, Ikebukuro, Tokyo, Japan, August 31 - September 4, 1993 /invited talk/

A. Badzian "Issues on Epitaxial Growth of Diamond " NIRIM International Symposium on Advanced Materials '94, Tsukuba, Japan, March 13-17, 1994 (invited talk)

A. Badzian "Diamond Nucleation and Epitaxy" 1994 March Meeting of the American Physical Society, Pittsburgh, Pa, 21-25 March 1994, /invited talk, session chairman/

A. Badzian and T. Badzian "Nucleation of Diamond in Metal-Carbon-Hydrogen Environment" International Conference on Metallurgical Coatings and Thin Films, April 25-29, 1994, San Diego, Ca / session chairman /

A. Badzian "Diamond Epitaxy" Second International Symposium on Diamond Films 3-5 May 1994, Minsk, Belarus / invited; member of Program Committee /

A. Badzian , T Badzian "Defects of CVD Diamonds", 8th CIMTEC Forum on New Materials , Florence, Italy, June 28-July 4, 1994 / invited, session chairman/

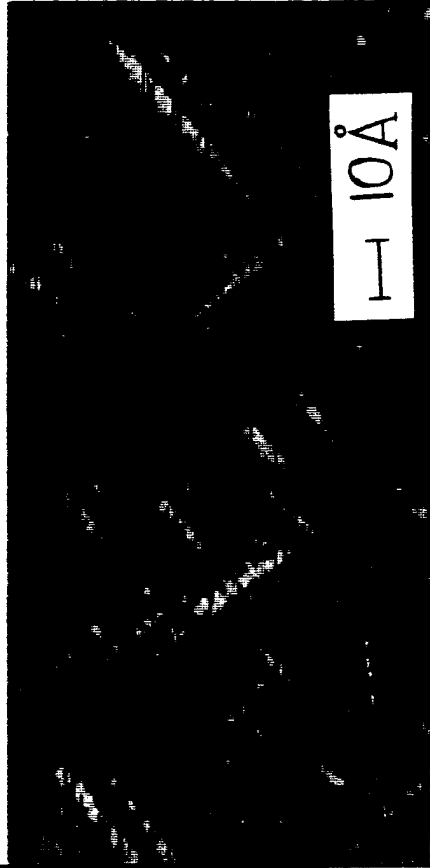
A. Badzian , "Diamond Homoepitaxy", The 4-th International Conference on the New Diamond Science and Technology ICNDST-4, July 18-22, 94, Kobe , Japan / invited; member of Program Committee /

A. Badzian and R. Roy, "Diamond Films: State of Science and Technology" AFOSR/URI Carbon/Carbon Composites Conference and the Carbon Research Centre Symposium, University Park, PA, September 13-14, 1994

# DEVELOPMENT OF THIN FILM DIAMOND BASED INTEGRATED CIRCUIT TECHNOLOGY

P.I.: A. Badzian and G. Sh. Gildenblat  
The Pennsylvania State University

## STM image of reconstructed (001) surface of boron doped diamond homoepitaxial film



## Approach

- \* Microwave plasma assisted chemical vapor deposition synthesis of diamond films and crystals
- \* Experimental studies of growth mechanisms and doping
- \* Experiments on heteroepitaxy on cBN, Ni on Cu, Si and SiC
- \* Develop technological steps to fabricate diamond-based devices
- \* Demonstrate feasibility of high temperature operation of thin film diamond devices

## Contract Objective

- \* To fabricate diamond transistor on single crystal heteroepitaxial diamond
- \* To fabricate small-scale IC operational at 400-500°C
- \* To obtain electronic grade diamond films on diamond and non-diamond substrates

## Progress

- \* Demonstrated heteroepitaxy of diamond on cBN over the area of 250  $\mu\text{m}$ .
- \* Demonstrated nearly perfect diamond films with characteristics of type IIa natural diamond
- \* Nucleation of diamond on Ni and suppression of graphite conucleation
- \* High temperature (>1200°C) growth of high quality diamond films on (001) and 1.2 mm single crystal on (110)
- \* Developed ECR etching method with no substrate bias
- \* Fabricated several recessed-gate MOSFETs using ECR etching process. Devices are operational in the 300-650K temperature range
- \* Developed analytical model of long channel diamond MOSFET

# **SINGLE CRYSTAL DIAMOND**

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- \* Single crystal growth without secondary nucleation has been demonstrated for (110) epitaxy
- \* No secondary nucleation disturbing epitaxy was observed over the area of diamond substrate 4x4mm
- \* Gem quality crystals have been grown
- \* The films are transparent
- \* The bulk crystal grown during three weeks has a height of 1.2mm

# **ELECTRONIC QUALITY CVD DIAMOND FILMS**

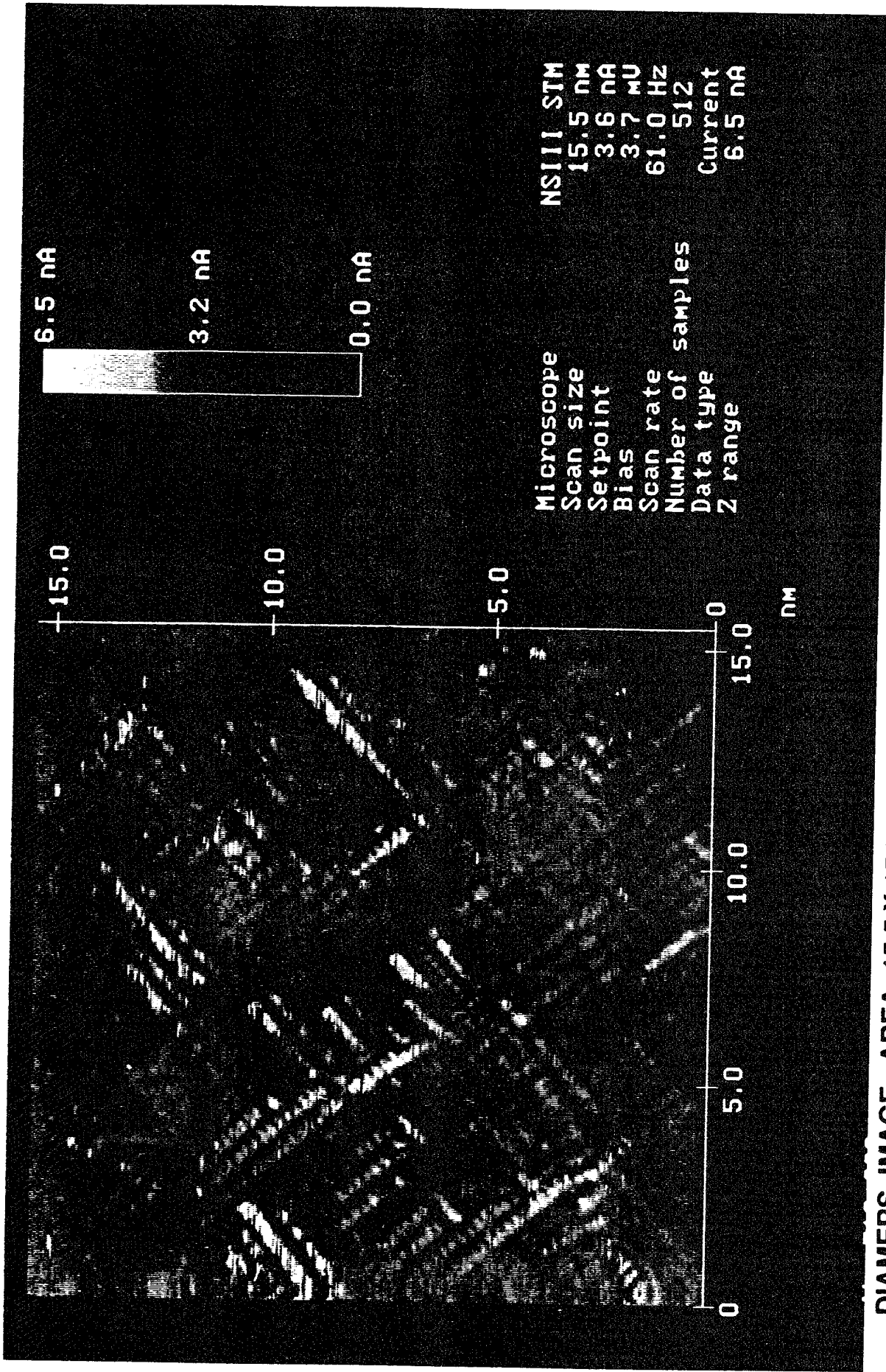
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Electronic films were grown on (001) substrates and the following studies were conducted:

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- \* Parametric studies
- \* Role of substrate surface misorientation (off angle cut)
- \* Lattice defects by Reflection High Energy Electron Diffraction (RHEED) and Scanning Tunneling Microscopy (STM)
- \* Oxygen plasma treatment of diamond surface prior to Schottky diodes fabrication
- \* Control over rectifying contacts is expected to be reached when density of lattice defects will be decreased

STM IMAGE of HYDROGENATED (001) SURFACE of BORON DOPED  
CVD DIAMOND FILM



DIAMERS IMAGE, AREA 15.5 X 15.5 nm

CVD by A. BADZIAN and T. BADZIAN  
STM by Y. KUANG and T.T. TSONG

# SURFACE MORPHOLOGIES OF HOMOEPITAXIAL (001) DIAMOND FILMS WITH MISORIENTATION ANGLES

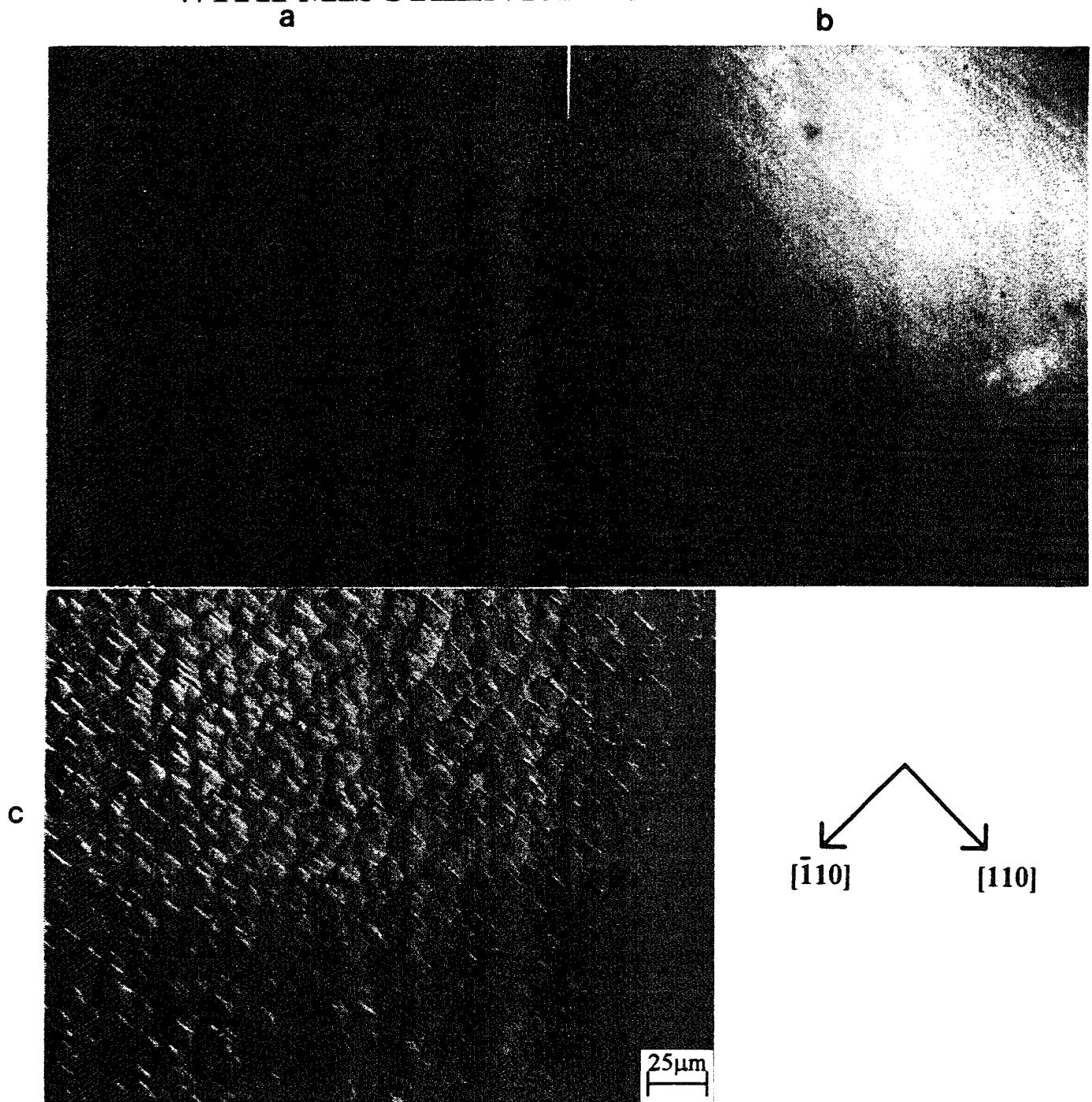


Fig. 2. DICM images of the surface morphologies of epitaxial diamond films grown on (a)  $0.1^\circ$ , (b)  $3.5^\circ$ , and (c)  $11.0^\circ$  off (001) substrates at  $1200^\circ\text{C}$ , 90 torr and 1 %  $\text{CH}_4$  in  $\text{H}_2$  for 5 hrs in (a) and 8 hrs in (b) and (c).

## RHEED OF HOMOEPITAXIAL (001) DIAMOND FILMS

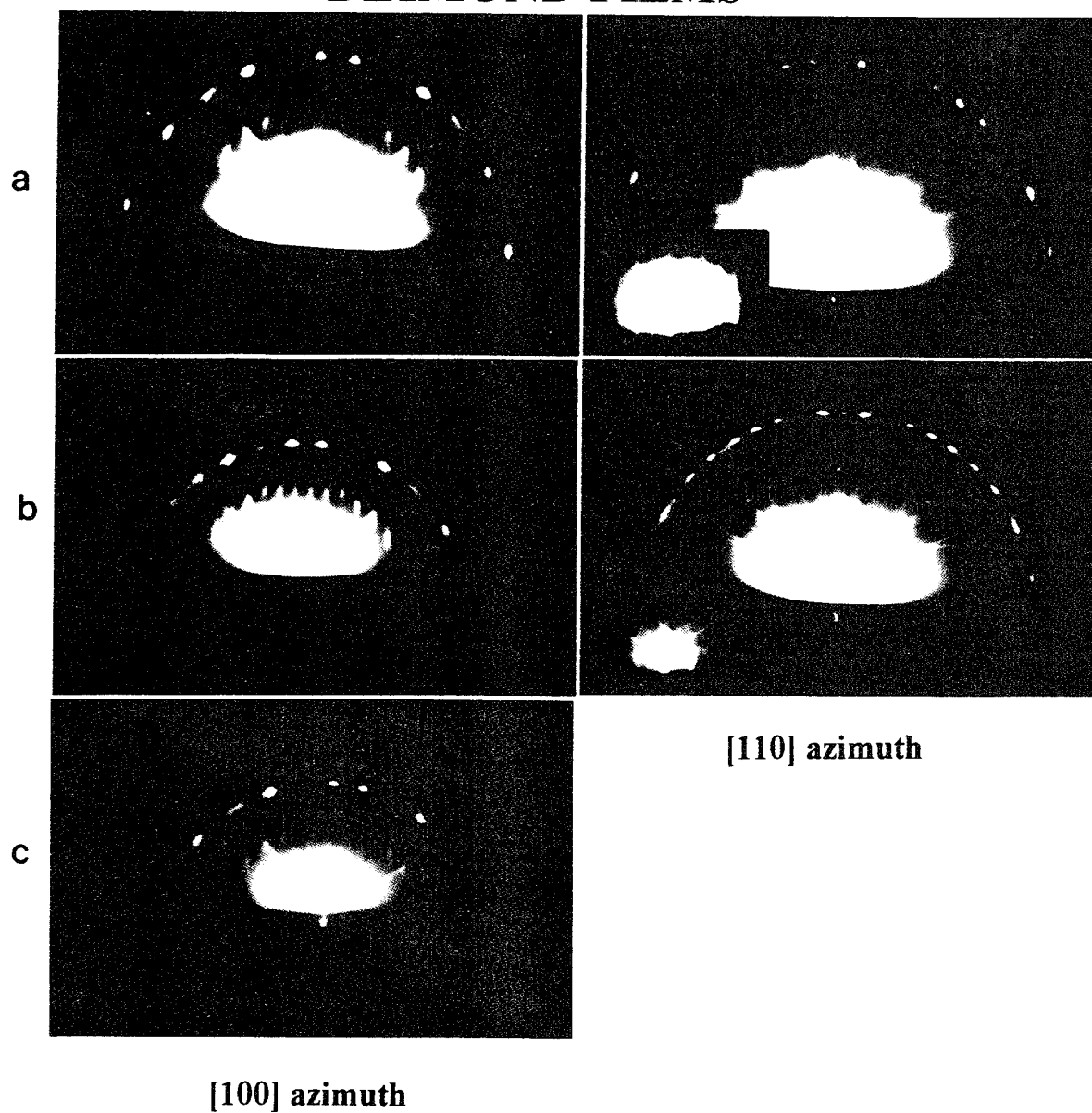


Fig. 3. RHEED patterns of the (001) film surfaces grown on (a)  $0.1^\circ$ , (b)  $3.5^\circ$ , and (c)  $11.0^\circ$  off substrates at the condition specified in Fig. 2, taken from [100] for the left and [110] azimuths for the right patterns at 40 kV. The insets of [110] azimuthal patterns show magnified views of the zeroth Laue zone.

## CONCLUSIONS

- 1 On the well-oriented (001) diamond substrate, growth hillocks are formed by two-dimensional nucleation and lateral migration of the newly created steps due to the lack of surface steps. On the other hand, the growth on the misoriented surface proceeds via step flow along the  $\langle 110 \rangle$  directions.
- 2 The growth on the  $3.5^\circ$  off substrate produced the smoothest surface from the surface roughness measurement.
- 3 RHEED showed that the films are single crystals and that their surfaces are composed of a two-domain  $2 \times 1$  reconstructed structure. RHEED also indicated that the  $3.5^\circ$  off film surface is the smoothest.