Diamond, Silicon Carbide and Related Wide Bandgap Semiconductors

Symposium held November 27-December 1, 1989, Boston, Massachusetts, U.S.A.

EDITORS:

J.T. Glass
North Carolina State University, Raleigh, North Carolina, U.S.A.

R. Messier
Pennsylvania State University, University Park, Pennsylvania, U.S.A.

N. Fujimori
Sumitomo Electric Industries, Ltd., Itami, Hyogo, Japan

SPONSORS

Air Products and Chemicals Company
Diamond Materials, Inc.
Kobe Steel, Ltd.
Norton Company
Sumitomo Electric Industries, Ltd.
## Contents

**PREFACE**

**MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS**

**PART I: INTRODUCTION TO DIAMOND FOR ELECTRONICS**

*THE ELECTRONIC AND OPTICAL PROPERTIES OF DIAMOND; DO THEY FAVOUR DEVICE APPLICATIONS?*

Alan T. Collins

*GROWTH OF DEVICE-QUALITY HOMOEPIXTAXIAL DIAMOND THIN FILMS*

M.W. Geis

*EPITAXIAL GROWTH OF DIAMOND AND DIAMOND DEVICES*

Naoji Fujimori, Takahiro Imai, Hideaki Nakahata, Hiromu Shiomi, and Yoshiki Nishibayashi

*ELECTRONIC PROPERTIES OF DIAMOND/NICKEL AND DIAMOND/BORON NITRIDE INTERFACES*

Warren E. Pickett and Steven C. Erwin

STATUS OF 6-SiC, DIAMOND AND C-BN SEMICONDUCTORS; COMPARISON OF A Si POWER FET TO A HYPOTHETICAL DIAMOND FET

Richard Koba and William Russell

*SIMPLE GRAPHITIC NETWORK MODELS OF "DIAMONDLIKE" CARBON*

Michael A. Tamor and Ching-Hsong (George) Wu

**PART II: DIAMOND GROWTH**

*SYNTHESIS OF METASTABLE DIAMOND*

Thomas R. Anthony

THERMODYNAMICS AND THE CVD OF DIAMOND

Walter A. Yarbrough

STUDIES OF DIAMOND GROWTH MECHANISMS IN A HOT FILAMENT REACTOR

C. Judith Chu, Benjamin J. Bai, Mark P. D'Evelyn, Robert H. Hauge, and John L. Margrave

ADSORPTION OF HYDROCARBON RADICALS ON THE HYDROGENATED DIAMOND SURFACE

Mark R. Pederson, Koblar A. Jackson, and Warren E. Pickett

MICROWAVE CVD OF DIAMOND USING METHANOL-RARE GAS MIXTURES

M. Buck, T.J. Chuang, J.H. Kaufman, and H. Seki

*Invited Paper*
LASER ASSISTED TECHNIQUES FOR DIAMOND AND DIAMONDLIKE THIN FILMS

REGROWTH OF DAMAGED LAYERS IN DIAMOND PRODUCED BY ION IMPLANTATION

SELECTIVE NUCLEATION OF SINGLE CRYSTAL CVD DIAMOND AND ITS APPLICABILITY TO SEMICONDUCTOR DEVICES
H. Kawarada, J.S. Ma, T. Yonehara, and A. Hiraki

THEORY AND EXPERIMENT: DEFECT STABILIZATION OF DIAMOND FILMS THROUGH MULTIPLE-REGROWTH
Y. Bar-Yam and T.D. Moustakas

PART III: CHARACTERIZATION AND PROPERTIES OF DIAMOND

NUCLEAR MAGNETIC RESONANCE SPECTROSCOPY IN THE STUDY OF DIAMOND THIN FILMS
Karen Mary McNamara, K.K. Gleason, and M.W. Geis

PREDICTED INFRARED SPECTRUM AND X-RAY DIFFRACTION PATTERNS FOR DIAMOND POLYTYPES
Andrew W. Phelps, William Howard, William B. White, Karl E. Spear, and D. Huang

DOMAIN SIZE DETERMINATION IN DIAMOND THIN FILMS

CHARACTERIZATION OF THIN FILM AND SINGLE-CRYSTAL CVD DIAMOND BY ABSORPTION AND LUMINESCENCE SPECTROSCOPY
A.T. Collins, M. Kamo, and Y. Sato

EFFECT OF DOPING WITH NITROGEN AND BORON ON CATHODOLUMINESCENCE OF CVD-DIAMOND
Y. Yokota, H. Kawarada, and A. Hiraki

PHOTOLUMINESCENCE SPECTROSCOPY OF DIAMOND FILMS
J.A. Freitas, Jr., J.E. Butler, S.G. Bishop, W.A. Carrington, and U. Strom

CW FOUR-WAVE MIXING IN SYNTHETIC DIAMOND
D.A. Redman and S.C. Rand

OPTICAL CHARACTERIZATION OF NICKEL IN DIAMOND
Maria Helena Nazaré, A.J. Neves, and Gordon Davies

A STUDY OF THE ELECTRONIC STRUCTURE NEAR INDIVIDUAL DISLOCATIONS IN DIAMOND BY ENERGY-LOSS SPECTROSCOPY
J. Bruley and P.E. Batson

CHARACTERIZATION OF HEAVY METAL CONTAMINATION IN DIAMOND FILMS USING SIMS, TXRF, AND RBS
R.S. Hockett and James Knowles
INFRARED CHARACTERIZATION OF THE HYDROGEN ENVIRONMENTS IN DIAMOND THIN FILMS 267

IN-SITU CHARACTERIZATION OF THIN POLycRYSTALLINE DIAMOND FILM QUALITY BY THERMAL WAVE AND RAMAN TECHNIQUES 273
R.W. Pryor, P.K. Kuo, L. Wei, R.L. Thomas, and P.L. Talley

INTRA- AND INTERGRANULAR FRACTURE OF DIAMOND THIN FILMS 279
H.A. Hoff, A.A. Morrish, W.A. Carrington, J.E. Butler, and B.B. Rath

FAR-INFRARED SPECTROSCOPY STUDY OF DIAMOND FILMS 285

LASER EMISSION FROM NATURAL DIAMONDS 291
Lucilia Santos and Estela Pereira

PART IV: DIAMOND ELECTRICAL PROPERTIES, CONTACTS AND DEVICES

ELECTRICAL PROPERTIES OF HOMOEPIXTAXIAL DIAMOND FILMS 297
G.Sh. Gildenblat, S.A. Grot, C.W. Hatfield, C.R. Wr0nski, A.R. Badzian, T. Badzian, and R. Messier

ELECTRICAL PROPERTIES OF THIN FILM AND BULK DIAMOND TREATED IN HYDROGEN PLASMA 303
Sacharia Albin and Linwood Watkins

DEEP LEVEL TRANSIENT SPECTROSCOPY STUDY OF THIN FILM DIAMOND 309
K. Srikanth, S. Ashok, W. Zhu, A. Badzian, and R. Messier

N-TYPE DOPING AND DIFFUSION OF IMPURITIES IN DIAMOND 315
S.A. Kajihara, A. Antonelli, and J. Bernholc

DOING OF DIAMOND BY CO-IMPLANTATION WITH DOPANT ATOMS AND CARBON 321
G.S. Sandhu, C.T. Kao, M.L. Swanson, and W.K. Chu

CYCLIC-CLUSTER MINDO/3 COMPUTATIONS OF THE LATTICE CONSTANT AND BAND STRUCTURE OF BORON NITRIDE, DIAMOND AND SILICON CARBIDE 327
Lawrence C. Snyder, Arthur H. Edwards, and Peter Deak

ELECTRICAL CHARACTERIZATION OF METAL CONTACTS ON DIAMOND THIN FILMS 333
Dario Narducci, Jerome J. Cuomo, C. Richard Guarnieri, and Stanley J. Whitehair
ELECTRICAL CONTACTS TO POLYCRYSTALLINE B DOPED DIAMOND FILMS
K. Nishimura, K. Das, M. Iwase, J.T. Glass, and K. Kobashi 341

METALLIZATION OF SEMICONDUCTING DIAMOND: Mo, Mo/Au AND Mo/Ni/Au
K.L. Moazed, J.R. Zeidler, and M.J. Taylor 347

PROPERTIES OF CVD DIAMOND/METAL INTERFACE
Yusuke Mori, Hiroshi Kawarada, and Akio Hiraki 353

BLUE LIKE DIAMOND LIGHT EMITTING DEVICES TO BE MASS-PRODUCED
M. Kadono, S. Hayashi, N. Hirose, K. Itoh, T. Inushima, and S. Yamazaki 359

ELECTRICAL BEHAVIOR OF DIFFUSED IMPURITIES IN DIAMOND SINGLE CRYSTALS
Dario Narducci and Jerome J. Cuomo 365

A DIAMOND SILICON HETEROJUNCTION DIODE
C.L. Ellison, R.M. Cohen, and J.T. Hoggins 371

CARBON-SILICON HETEROJUNCTION DIODES FORMED BY CH₄/Ar rf PLASMA THIN FILM DEPOSITION ON Si SUBSTRATES

DOPING EFFECT IN HYDROGENATED AMORPHOUS CARBON THIN FILMS BY ION IMPLANTATION
S.P. Wong and Shaoqi Peng 383

OPTICAL BAND GAP OF DIAMOND-LIKE CARBON FILMS AS A FUNCTION OF RF SUBSTRATE BIAS
P.W. Pastel and W.J. Varhue 389

PART V: GROWTH AND CHARACTERIZATION OF SILICON CARBIDE

*STEP-CONTROLLED EPITAXIAL GROWTH OF SiC
Hiroyuki Matsunami, Tetsuzo Ueda, and Hironori Nishino 397

LOW TEMPERATURE METAL ORGANIC CHEMICAL VAPOR DEPOSITION (LTMOCVD) OF ELECTRONIC MATERIALS
Alain E. Kaloyeros, Paul J. Toscano, Richard B. Rizk, Victor Tulchinsky, and Alex Greene 409

GROWTH OF 6H-SiC ON CVD-GROWN 3C-SiC SUBSTRATES
Woo Sik Yoo and Hiroyuki Matsunami 415

DOPED AMORPHOUS SiC, MIXED CARBIDE AND OXYCARBIDE THIN FILMS BY A LIQUID ROUTE
C-J Chu, E. Liimatta, and J.D. Mackenzie 421

*Invited Paper
LIQUID PHASE HOMOEPIXTALICGROWTH OF 4H-SiC CRYSTALS
AND FABRICATION TECHNIQUES OF BLUSH-PURPLE LIGHT-
EMITTING DIODES
Y. Ueda, T. Nakata, K. Koga, Y. Matsushita,
Y. Fujikawa, T. Uetani, T. Yamaguchi, and T. Niina

LOW TEMPERATURE SELECTIVE GROWTH OF β-SiC USING
SiH₂Cl₂/C₃H₆/HCl/H₂ GAS SYSTEM
Y. Ohshita

INFRARED STUDY OF AMORPHOUS-CRYSTALLINE PHASE TRANSITION
IN AN ANNEALED AMORPHOUS HYDROGENATED SILICON-CARBON
ALLOY FILM
D.K. Basa and F.W. Smith

THE FORMATION OF HELICAL DISLOCATIONS IN SILICON
SUBSTRATES DURING EPITAXIAL DEPOSITION OF β-SiC
M. Aindow, T.T. Cheng, and P. Pirouz

GROWTH OF EPITAXIAL SiC LAYERS ONTO ON- AND OFF-AXIS
6H-SiC SUBSTRATES BY ION BEAM DEPOSITION

SEM OBSERVATION OF GROWTH AND DEFECT FORMATION OF
HETEROEPIXTALICALLY GROWN SiC ON (100) SILICON
B. Molnar and L.M. Shirey

PART VI: SILICON CARBIDE: ELECTRICAL
PROPERTIES, CONTACTS, AND DEVICES

*EPITAXIAL THIN FILM GROWTH AND DEVICE DEVELOPMENT IN
MONOCRUSTALINE ALPHA AND BETA SILICON CARBIDE
Robert F. Davis, J.W. Palmour, and J.A. Edmond

NATIVE DEFECTS, DIFFUSION, SELF-COMPENSATION, AND
BORON DOPING IN CUBIC SILICON CARBIDE
C. Wang, J. Bernholc, and R.F. Davis

*SOME OBSERVATIONS ON THE ELECTRICAL CHARACTERIZATION OF
THE HETEROEPIXTALICALLY GROWN CUBIC SiC
B. Molnar and G. Keiner

DEEP-LEVEL DOMINATED ELECTRICAL CHARACTERISTICS OF Au
CONTACTS ON β-SiC
K. Das, H.S. Kong, J.B. Petit, J.W. Bumgarner,
L.G. Matus, and R.F. Davis

A NEW DEEP ACCEPTOR IN EPITAXIAL CUBIC SiC
J.A. Freitas Jr. and S.G. Bishop

ELECTRONIC STRUCTURE OF WIDE BANDGAP SEMICONDUCTOR
INTERFACES: CUBIC SiC/AlN, SiC/BP, C/BN
W.R.L. Lambrecht and B. Segall

OHMIC CONTACTS ON β-SiC
M.I. Chaudhry, W.B. Berry, and M.V. Zeller

*Invited Paper
PART VII: OTHER WIDE BANDGAP SEMICONDUCTORS

*PERSPECTIVE ON GALLIUM NITRIDE
Jacques I. Pankove 515

GROWTH OF HIGH-RESISTIVITY WURTZITE AND ZINCBLENDE
STRUCTURE SINGLE CRYSTAL GaN BY REACTIVE-ION MOLECULAR
BEAM EPITAXY
R.C. Powell, G.A. Tomash, Y.-W. Kim, J.A. Thornton,
and J.E. Greene 525

MICROSTRUCTURAL AND OPTICAL CHARACTERIZATION OF GaN
Films grown by PECVD on (0001) SAPPHIRE SUBSTRATES
T.P. Humphreys, C.A. Sukow, R.J. Nemanich,
J.B. Posthill, R.A. Rudder, S.V. Hattangady, and
R.J. Markunas 531

STRUCTURAL DEFECTS IN GaN EPILAYERS GROWN BY GAS SOURCE
MOLECULAR BEAM EPITAXY
Z. Sitar, M.J. Paisley, B. Yan, and R.F. Davis 537

*CUBIC BORON NITRIDE CRYSTALS GROWN AT HIGH PRESSURE: pn
JUNCTION, CRYSTALLOGRAPHIC POLARITY AND SOME PROPERTIES
Osamu Mishima 543

CUBIC BORON NITRIDE AS A NEW SEMICONDUCTOR FOR OPTO-
ELECTRONICS: LUMINESCENCE PROPERTIES AND POTENTIALITIES
Koh Era and Osamu Mishima 555

VIBRATIONAL SPECTROSCOPY OF BORON NITRIDE AT HIGH
TEMPERATURES AND Pressures
Gregory J. Exarhos and Nancy J. Hess 561

GROWTH AND PHYSICAL PROPERTIES OF rf-MAGNETRON SPUTTERED
InN SEMICONDUCTING FILMS
W.A. Bryden, J.S. Morgan, T.J. Kisternacher,
D. Dayan, R. Fainchtein, and T.O. Poehler 567

SUBSTRATE AND TEMPERATURE DEPENDENT MORPHOLOGY OF rf-
SPUTTERED INDUM NITRIDE FILMS
T.J. Kisternacher, D. Dayan, R. Fainchtein,
W.A. Bryden, J.S. Morgan, and T.O. Poehler 573

ELECTRON MICROSCOPY OF InN FILMS
J.S. Morgan, T.J. Kisternacher, W.A. Bryden, and
T.O. Poehler 579

*BORON PHOSPHIDE AS A REFRACTORY SEMICONDUCTOR
Y. Kumashiro, M. Hirabayashi, and S. Takagi 585

THERMAL AND ION BEAM INDUCED REACTIONS IN Ni ON BP
Naoto Kobayashi, Yukinobu Kumashiro, Peter Revesz,
Jian Li, and James W. Mayer 595

BORON PHOSPHIDE ON SILICON FOR RADIATION DETECTORS
J.C. Lund, F. Olschner, F. Ahmed, and K.S. Shah 601

*Invited Paper