TR 90003
FEBRUARY

SECOND QUARTER TECHNICAL REPORT

DEVELOPMENT OF HIGH PERFORMANCE β-SiC FIELD-EFFECT TRANSISTORS

Prepared by

Diamond Materials, Inc.
2820 East College Avenue
State College, PA 16801

February 14, 1990

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Contract No. N00014-89-C-0207

Research Supported by:

Strategic Defense Initiative/Innovative Science and Technology and Managed by Office of Naval Research

Diamond Materials Institute

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: Unclassified	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S): TR 90003	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION: Diamond Materials, Inc. / 6b OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: Office of Naval Research
6c. ADDRESS (City, State, and ZIP Code): 2820 East College Avenue, State College, PA 16801	7b. ADDRESS (City, State, and ZIP Code): Code 1114, 800 N. Quincy Street, Arlington, VA 22217-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: SDIO/IST/SBIR / 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code): The Pentagon, Washington, DC 20301-7100	10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO
63220C	SDIO/IST/SBIR	S405010	ssr02

11 TITLE (Include Security Classification): Development of High Performance β-SiC Field-Effect Transistor

12 PERSONAL AUTHOR(S): Richard Koba

13a. TYPE OF REPORT	13b. TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Quarterly Technical	FROM 89/10/21 TO 90/1/20	1990 February 14	5

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	silicon carbide, chemical vapor deposition, heteroepitaxy

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

During the last three months of this Phase II program, Diamond Materials, Inc. (DMI) has: (1) finished major equipment installations, (2) identified a potentially superior source gas for β-SiC CVD, and (3) instituted an equipment inventory and maintenance system in compliance with Federal Acquisition Regulations (FARs). All proposed engineering upgrades to DMI's β-SiC CVD reactor have been installed and tested. DMI has installed its activated reactive evaporation (ARE) reactor which will be be used for the deposition of cubic AlN and MgO dielectric films on β-SiC. DMI has also installed a hot wall tube furnace which will be used for thermal oxidation of β-SiC crystals to form SiO_2. DMI has identified a proprietary source gas for the heteroepitaxial growth of β-SiC on TiC substrates. This source gas promises to be greatly superior to the gas DMI is currently using, viz., methyltrichlorosilane (MTS). Use of MTS will probably hinder controlled *in situ* doping of β-SiC epi layers. DMI has identified a highly capable, specialty chemical company willing to synthesize and purify this source gas. DMI has written a proposal to a certain, large company requesting funding to develop this source gas. If this source gas is developed by private funding, then it will be acquired for use on this Government contract. DMI has also instituted an

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

inventory and maintenance procedure for equipment purchased with Government funds, in compliance with FARs. During the next three months, DMI will grow heteroepitaxial β-SiC films on TiC substrates. DMI will characterize these films and will strive to minimize the areal density of crystallographic defects and the background carrier concentration in the β-SiC. Synthesis of highly pure (uncompensated), low defect concentration β-SiC epi layers on TiC will be the key to the fabrication of high performance β-SiC FETs.

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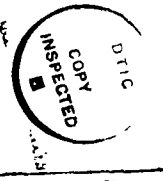

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SECOND QUARTER TECHNICAL PROGRESS REPORT

DEVELOPMENT OF HIGH PERFORMANCE β-SiC FIELD-EFFECT TRANSISTORS

1. INTRODUCTION

DMI was awarded an SBIR Phase II program entitled "Development of High Performance β-SiC Field-Effect Transistors." This 24-month program officially started July 20, 1989. This Technical Progress Report summarizes the accomplishments made during the second quarter of this program, that is, from October 21, 1989, through January 20, 1990.

The ultimate goal of this Phase II program is to develop β-SiC field-effect transistors. These β-SiC transistors should be of sufficient quality to enable measurement of β-SiC transistor characteristics at *high frequencies* for the first time. To achieve these goals, DMI's Phase II program includes the following tasks:

1. Improve the quality of undoped, monocrystalline β-SiC films grown on TiC substrates. Crystallographic defect density and background carrier concentrations must be minimized to achieve acceptable FET transconductance.
2. Develop methods to *in situ* dope β-SiC during CVD growth.
3. Evaluate and compare three different dielectrics as possible gate insulators for β-SiC IGFETs.
4. Fabricate β-SiC MESFETs.
5. Fabricate depletion mode and enhancement mode β–SiC IGFETs using a previously optimized gate insulator.

2. ACCOMPLISHMENTS OF THE LAST QUARTER

2.1 Completed Installations

During the last three months, all of the proposed modifications to DMI's baseline β-SiC CVD reactor were installed. The gas control system was expanded to handle eight different gases. A new belljar assembly has been installed consisting of two, concentric fused silica tubes. A novel sealing system at both ends of the tubes permits the flow of cooling water between the tubes. Since the tubes are stock items, damaged tubes can be quickly and inexpensively replaced. A spinning, inverted platen

assembly with a Ferrofluidics feed-through has been tested. This assembly is capable of spinning 1 cm diameter or 5 cm diameter substrates at rates up to 100 rpm. The susceptor itself uses low emittance, machined ceramic parts to sandwich a TiC substrate next to the graphite susceptor. The substrate can be controllably heated up to 1500°C using the same 10 kW, 450 kHz power supply used in Phase I. The optical pyrometer used to measure substrate surface temperature has been calibrated by noting *in situ* the melting point of Si.

DMI has also finished the installation of a hot wall tube furnace capable of reaching 1200°C over a "flat zone" 25 cm long. (This furnace was purchased with Company funds). During the latter tasks of this program, the tube furnace will be used to grow SiO_2 films on ß-SiC by wet oxidation. This tube furnace has been installed with a new fused silica tube and is equipped with a special silica "boat" capable of handling 1 cm diameter TiC substrates.

DMI's activated reactive evaporation (ARE) system was installed in State College. This ARE reactor was designed and built using Company funds. DMI is vigorously working to develop a process to deposit cubic boron nitride (c-BN) thin films by ARE. To date, DMI has produced hard, boron nitride films which are apparently tetrahedrally bonded, with a low concentration of graphitic component. DMI is currently working to produce films which are 100% c-BN. Knowledge acquired by learning how to stabilize the cubic (zinc blende) polymorph of boron nitride will then be applied to the synthesis of cubic AlN on ß-SiC substrates. Future tasks in this Phase II program will use the ARE reactor to synthesize cubic AlN and MgO films on ß-SiC substrates. AlN and MgO will be compared to SiO_2 as a gate dielectric for ß-SiC insulated gate field effect transistors (IGFETs).

2.2 Alternative Source Gas Identified

In Phase I, DMI successfully used methyltrichlorosilane (CH_3SiCl_3) to grow heteroepitaxial ß-SiC films on TiC by CVD. However, the use of MTS was problematic for two reasons: (1) the nucleation of the ß-SiC films on TiC had to occur rapidly in order to prevent etching of the TiC substrate by hydrochloric acid. Rapid nucleation of ß-SiC films tends to generate crystallographic defects in the epi layers. (2) The highly corrosive nature of MTS tended to clog its mass flow controller.

Simple thermochemical calculations indicate that the presence of chlorine or HCl during ß-SiC growth would make *in situ* doping difficult to achieve. DMI plans to use diborane as the dopant gas for boron. However, the boron may be gettered by

chlorine to form boron trichloride. Additionally, DMI was planning to use ammonia as the source of donor doping with nitrogen. However, the combination of ammonia vapor with hydrogen chloride usually results in the formation of ammonium chloride powder.

During the last quarter, DMI has identified an alternative, and potentially superior source gas for ß-SiC CVD. This source gas should overcome the aforementioned limitations of methyltrichlorosilane (MTS). However, like MTS, this gas is a single-point source for SiC deposition. DMI has identified a certain specialty chemical company willing and able to develop this source gas as a proprietary product. Purification will be a special challenge since nitrogen (in all forms) must be selectively removed from the source gas to below ppm levels. Most commercially available source gases are not purified of N_2 because nitrogen is innocuous for most Si and GaAs processing. Routine detection of trace concentrations of nitrogen in silicon-containing chemicals is especially challenging since a mass spectrometer must have a mass resolution > 960 to distinguish between Si^+ and N_2^+. Fortunately, this specialty chemical company does possess the adequate know-how, purification reactors, and analytical instrumentation to purify the source gas of nitrogen.

With regards to this Phase II program, DMI firmly believes that the successful synthesis of ß-SiC FETs will be contingent upon the synthesis and purification of this proprietary source gas. DMI has written a proposal to a large company asking for financial support to fund the synthesis and purification of this proprietary source gas. DMI hopes that private funding can be obtained to synthesize and purify this source gas. Once the development costs have been sustained by the private sponsor, then DMI plans to use Government funds to purchase several tens of milliliters of this material for use in this Phase II program.

If this proprietary source gas development is <u>not</u> privately funded, then DMI may have to alter the statement-of-work in the Phase II by growing undoped ß-SiC films by the use of MTS, and then forming p-type and n-type layers by the use of ion implantation. DMI is reasonably certain that attempting to dope ß-SiC *in situ* during CVD using MTS will be futile.

2.3 Other Accomplishments

During the last three months, DMI has established an inventory control system in compliance with current Federal Acquisition Regulations. DMI was visited by Mr. John Aymold (Property Administrator, DCASR - Reading, PA) and Mr. John Kilhofer

(Defense Contract Administrator, Services Branch - State College, PA) who assisted DMI personnel in establishing correct inventory procedures. Since their visit, DMI has completed inventory of all equipment purchased on this Government contract, and has instituted a maintenance and calibration program for this equipment.

During the last quarter, DMI submitted a purchase order to Gesellschaft für Technische Thermochemie und-Physik mbh in Aachen, West Germany, for the SAGE computer program. DMI anticipates to receive 5.25" diskettes with the SAGE computer program within the next month.

3. GOALS FOR THE NEXT QUARTER

During the next three months, DMI plans to achieve the following:

1. Install the SAGE thermochemical computer model. Use it to model the thermochemical interaction between TiC, β-SiC, H_2, Ar, MTS, HCl, diborane and ammonia at the growth temperatures a function of temperature and partial pressure. DMI will work closely with its consultant, Prof. Karl Spear of Penn State University, during the installation and de-bugging of SAGE.

2. Obtain an improved source gas for β-SiC growth. If development of this source gas is funded by an outside company, DMI could have the first batch of this source gas as early as March 30, 1990. DMI will purchase a quantity of this source gas for use on this Government program and will use it to perform heteroepitaxial growth β-SiC on TiC. Unintentionally doped β-SiC epi layers will be grown using this source gas. The background carrier concentration in the epi layers will be measured. Background (uncompensated) carrier concentrations in β-SiC must be less than ≈ 5 x 10^{17}/cc in the channel layers of FETs in order to achieve reasonable frequency response and transconductance.

3. If the novel source gas proves superior, then DMI will initiate *in situ* doping experiments to dope β-SiC films with B, Al, and N to controlled levels. DMI will also characterize these films by measurement of carrier concentration.

4. The crystallographic quality of the β-SiC epi layers will be measured by x-ray diffraction techniques. The goal is to produce β-SiC epi layers free of dislocations, stacking faults and subgrain boundaries.

5. DMI will also design and construct a high temperature probe station to measure the electrical characteristics of β-SiC test structures at elevated temperatures.