(23) Energy Conservation Sciences for operation and Security of Large-Scale Systems

The objectives of the proposed effort are to expand and/or supplement the research presently underway as past of the Center on Security of Large Scale Systems. In particular, the project will seek to (1) expand solid-state research in the area of Silicon Carbide (SiC) for the purpose of reducing size, weight, and cost of power converters for motor drives and distributed generation, (2) to investigate methods of motor control including the advantages of SiC devices to increase the efficiency and reduce the cost of electric drives, and (3) to incorporate the results of the Center's research in fuel cell testing and modeling to suggest design and operation of these devices in distributed generation during islanding of an Electric power Grid.

Total project cost: $322,834
Funding request: $249,999
Project Lead: Purdue University
Project Participants: Wright State University

Start Date: May 23, 2005
End Date: May 23, 2007

Presentations/Publications

None.

Patents

None.

Progress in Past Quarter and Current Status

Task 1 Silicon Carbide Devices for Advanced, High-Efficiency Power Conversion

Michael Capano, Purdue University

Objectives:

The objectives of the SiC component of this research are to (1) develop criteria for the selection of SiC SBDs or PiN diodes and, (2) examine power dissipation and cooling requirements needed for SiC electronics.

Background:

To accomplish these objectives, simulation of SiC diodes will be undertaken using *Medici*, with the purpose of designing PiN and SBD diodes with nominally equivalent voltage ratings. Selection of PiN and SBDs will be based on simulations using total power dissipation as the criterion for selection. Also, these simulations serve the purpose of defining device structures to be examined experimentally. Two voltage regimes are to be investigated theoretically: 1000 V and 5000 V. PiN diodes and Schottky diodes nominally in the 1000 V range will be fabricated and their electrical and thermal characteristics shall be compared. All activities to be performed under this project fall into one of the four categories below:

1. Design system requirements for SiC diodes, including selection of adequate coolant. SiC PiN and Schottky diodes with similar voltage ratings (1500 V and 5000 V).
2. Build SiC PiN and Schottky diodes. Measure diode characteristics under forward (on-state) and reverse (off-state) bias conditions.
3. Develop selection criteria for choosing PiN or SBDs based on current rating, switching frequency and power density limitations.
4. Investigate cooling requirements for SiC devices.

Research Progress:

The objective for this quarter was to grow the epilayers needed for the 1000 V PiN diodes, having completed the fabrication of SiC Schottky diodes last quarter. A process flow for the PiN diodes is presented below. Devices with dimensions from 100 μm diameter up to 2 mm x 2 mm will be fabricated and tested. At this time, the low-doped, n-type layer that serves as the “intrinsic” layer has been grown. It is 6 μm thick with a nominal doping of approximately 5-6 x 10^{15} cm^{-3}, which enables it to block 1000 V as did the Schottky barrier diode previously built.

Table I. SiC p-i-n Diode Processing Outline

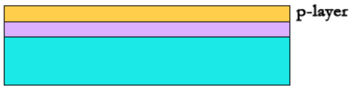
1 Receive Sample
Size: 3” wafer
Doping: n-type
Polytype: 4H-SiC
Orientation: 8.02˚
Resistivity: 0.020
Thickness: 395.0μm

2 Dice sample
Pieces: 6 of equal area
Cut: One parallel to major flat, Two parallel to minor flat

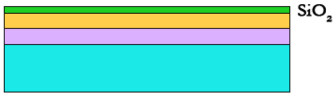
3 Clean sample
Method: Solvent and Piranha

4 Grow intrinsic layer
Method: CVD with Epigress
Thickness: 6μm

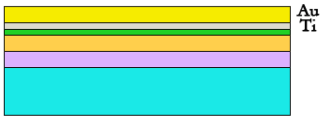
5 Grow p-type layer
Method: CVD with Epigress
Thickness: 1.16μm



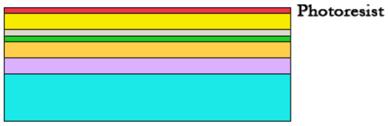
6 Deposit SiO_2 mask
Method: LPCVD with Tempress
Thickness: 500Å



7 Deposit metal mask
Method: E-Beam Evaporation
Layer 1: 100Å of Ti
Layer 2: 5000Å of Au

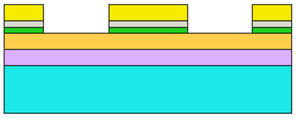


8 Photolithography of mesa mask
Photoresist: Positive (AZ-1518)
Develop: 5:1 (Water : AZ 351 Developer)
or 1:1 (Water : AZ Developer)



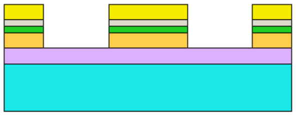
9 Wet etch mesa mask

Au Layer: TFA
Ti and SiO_2 Layer: BHF



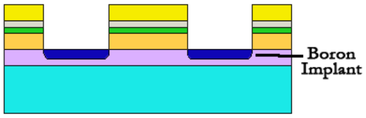
10 RIE p-type layer

Gas: SF_6
Pressure: ~$1\text{x}10^{-3}$ T
Power: 100W



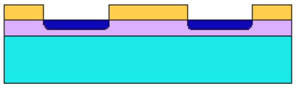
11 Ion implantation

Ion: Boron
Energy: 30keV
Dose: $1\text{x}10^{15}$ cm^{2}



12 Remove mesa mask with wet etch

Au Layer: TFA
Ti and SiO_2 Layer: BHF

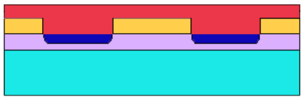


13 Anneal lattice damage from implantation

Temperature: 1050˚
Time: 90 minutes
Environment: Ar
Pressure: ~$1\text{x}10^{-6}$ T

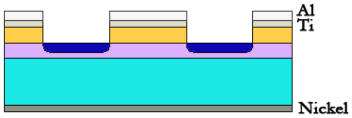
14 Photolithography of frontside contact mask

Photoresist: Positive (AZ-1518)
Develop: 5:1 (Water : AZ 351 Developer)
or 1:1 (Water : AZ Developer)



15 Deposit backside and frontside contacts

Method: E-Beam Evaporation
Backside Layer 1: 1500Å of Ni
Frontside Layer 1: 400Å of Ti
Frontside Layer 2: 1100Å of Al

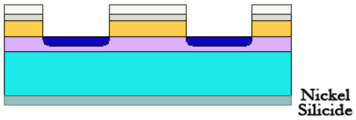


16 Lift-off frontside contacts

Method: Acetone soak

17 Anneal contacts

Temperature: 1000˚
Time: 2 minutes
Environment: Ambient



Pressure: $1\text{x}10^{-6}$ T

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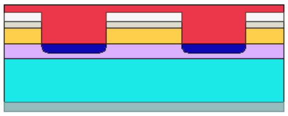
18 Photolithography of frontside contact mask

Photoresist: Positive (AZ-1518)
Develop: 5:1 (Water : AZ 351 Developer)
or 1:1 (Water : AZ Developer)



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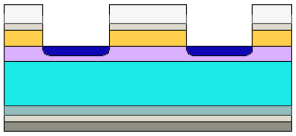
19 Deposit additional contact metal

Method: E-Beam Evaporation
Backside Layer 1: 100Å of Ti
Backside Layer 2: 5000Å of Ni
Frontside Layer 1: 5000Å of Al



20 Lift-off frontside contacts

Method: Acetone soak

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21 Electrical Characterization

Method: I-V Probing

All tools needed to complete the fabrication of the PiN diodes are now in place in the Birck Nanotechnology Center (BNC) except for the Epigress chemical vapor deposition (CVD) reactor. The CVD reactor is currently being moved from its old location in Purdue's electrical engineering building to the BNC. This is relevant because the tool will be used to anneal the implanted device termination in step 13. We anticipate the tool will be ready by January 31, 2007. Completion of the diodes is expected by end of February or mid March.

The objectives of the experimental device research are three-fold. First, a comparison of the transient characteristics of the devices will provide useful information about power dissipation and a proper choice of PiN vs Schottky diodes depending on operating frequency and total power dissipation. Second, the effectiveness of growth procedures to eliminate stacking faults in bipolar devices (e.g. the PiN diode) can be evaluated. Buffer layers grown prior to the intrinsic layer act to enable dislocations (line defects in the material) to convert from a basal plane configuration to a more benign threading edge configuration. Third, new processing steps employed in the fabrication of the Schottky diodes (elimination of Au, use of poly-Si implant mask, application of SiO_2 passivation) can be evaluated relative to the state of the art SBD processing technology. Fourth and most important, an attempt at measuring thermal characteristics of working devices will be made using optical techniques (Raman spectroscopy, FTIR). Such measurements, if successful, will provide direct information pertinent to the proper selection of SiC diodes for specific applications. Also, the data will be invaluable for refining thermal analysis of SiC devices through simulation using *Medici*.

Completion of fabrication and testing of 1000 V PiN diodes. Simulation of PiN diodes with 50 micron epilayers.

Task 2. Optimal Efficiency Motor Control Strategies

Marian Kazimierczuk, Wright State University

Objectives:

The objective of this part of the project was to design a dc/ac variable- frequency three-phase power inverter, using Si and SiC power devices, estimate the inverter power losses and efficiency, and compare the losses and efficiency with Si and SiC devices.

Background:

The benefits of silicon carbide devices include high-breakdown voltage, high-temperature, high-frequency, high-reliability, and nearly zero reverse recovery. In previous quarters, electrical and thermal characteristics of SiC power devices were studied and areas of applications were identified [1]. High-voltage SiC Schottky diodes appear to be the most promising SiC power devices for high-voltage high-frequency applications, such as rectifiers and clamp circuits in dc/dc power converters and power-factor correctors [2]. The use of theses diodes allows the designers to avoid snubber circuits and increase the switching frequencies. Also, parallel combinations of power Si MOSTETs and SiC diodes are very promising arrangements in many applications. A topology of the dc/dc inverter was selected and designed. A Class D half-bridge dc/ac power inverter was selected for further investigations and the circuit was designed.

[1] N. Das and M. K. Kazimierczuk, ``Applications of Silicon Carbide Power Devices in Power Electronics," Electrical Manufacturing and Coil Winding Association, Indianapolis, IN, September 18-20, 2006.

[2] D. Murthy and M. K. Kazimierczuk, ``Active Clamp Circuits for Flyback PWM DC-DC Converter," Electrical Manufacturing and Coil Winding Association, Indianapolis, IN, September 18-20, 2006.

Research Progress:

During this quarter, the ac/dc three-phase power conversion under the energy recovery operating conditions was studied. This mode of operation is part of the overall operation of the bidirectional inverter: dc-to-ac and ac-to-dc conversions. During the energy recovery time interval, the energy is transferred from the inverter ac output to the inverter dc input via rectification process. Silicon carbide Schottky diodes are connected in parallel with MOSFETs as so-called anti-parallel diodes. These diodes reduce the reverse recovery effect in the MOSFET body diodes when the energy is transferred from the dc input to the ac output and form a rectifier when the energy is transferred from the output to the input. Commercially available silicon carbide Schottky diodes were used in this study. Extensive simulations of a three-phase rectifier with Schottky silicon carbide diodes were performed to study the steady-state and dynamic performance of these diodes. The circuit was simulated using the commercial large-signal dynamic models of the SiC diodes. Switching characteristics of Schottky silicon carbide diodes were the main focus of this research. In addition, experiments for Schottky silicon carbide diodes were conducted at a low-power level at different frequencies. The simulations were also carried out for the rectifier with fast-recovery pn junction silicon diodes. The results were compared for the two types of diodes.

Plans for Next Quarter:

In the previous quarter, the performance of the Schottky silicon diodes were studied by simulation. The plans for the next quarter are to develop analytical equations to describe waveforms the Schottky silicon carbide diodes are turned off and turn on.

Task 3 Islanding and Distributed Generation for Enhanced Electric Power Grid Security

Academic Faculty:
Shripad Revankar, Associate Professor, Department of Nuclear Engineering, PU

Mitch Wolff, Professor, Department of Mechanical Engineering, WSU

Graduate Students:

Brian Wolf	M.S. Candidate Nuclear Engineering, PU
Karleine Justice	M.S. Candidate Mechanical Engineering, WSU
Carlos Gutierrez	M.S. Candidate Mechanical Engineering, WSU

Objective:

Investigate the control and performance of distributed generation during islanding of an electric power grid. High temperature fuel cell hybrid systems will be used for power generation.

Background:

Advancement in research of distributed generation of electrical power is a result of energy security issues and changing markets and technologies. Fuel cell hybrid technologies which integrate high temperature fuel cells with another power generation technology have promising abilities which make them an important research topic for development and commercialization. They meet many demands of U.S. energy goals of the future including independence from foreign sources, greater security, and pollution free emissions.

Previous work accomplished includes a thorough literature survey on hybrid fuel cell distributed generation systems. Steady state models for both Molten Carbonate Fuel Cells (MCFC) and Turbines of different capacities have been created. Other component models such as oxidizer, and heat exchangers have also been developed for steady state conditions. Certain controls were then implemented to begin the transition to dynamic modeling. Dynamic modeling of the fuel cell was successful and benchmarked with model results in literature. Multiple visits between Wright State and Purdue have proven to be very productive. Coupling of the MCFC fuel cell model and the turbine model has been a success.

Research Progress:

In the past quarter, Purdue visited Wright State on December 14th. The purpose of the visit was to complete a fuel pre-conditioner model. This helps to account for the fuel being pre-heated and mixed with steam before entering the fuel cell. This task was accomplished and has been implemented in the full multi-megawatt system model. Currently only one major task is left. This task involves finalizing the choices of control variables and incorporating PID type controllers to the system. As soon as this is accomplished, parametric studies can be performed and analyzed such as the effects of variation in the ambient temperature.

A Solid Oxide Fuel Cell model has been further developed. Specifically, an energy balance, and mass balances of the solid oxide fuel cell system have been produced and implemented into MATLAB/Simulink.

Plans for Next Quarter:

In the next quarter a complete dynamic controlled hybrid system will be completed. The tasks needed to reach this goal include adding coupling controls between the fuel cell system and turbine system. Also, it is expected that a Solid Oxide Fuel Cell model will be completed and working properly.