(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

The project is divided into three tasks. Progress and current status for each task are described in the following paragraphs.

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

Michael Capano, Purdue University

Summary of Research Plan

Depending on specific application requirements, a SiC Schottky barrier diode (SBDs) or SiC PiN diode may be an ideal choice for the application at hand. Selection of which device to use depends, however, on many factors including voltage rating, current density, on-state resistance, switching frequency, duty cycle, and power density limits. 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. 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: 1500 V and 5000 V. In addition to these simulations, experimental measurements from actual SiC diodes will be performed. 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

Last quarter the process flow for a SiC Schottky barrier diode (SBD) was presented, and work during that project period focussed on fabrication of 1500 V SiC SBDs (see Figure 1). The goal this quarter was to complete fabrication of the first lot of diodes and begin testing. However, significant delays have been incurred because of equipment downtime, and delays caused by moving processing equipment from the old Electrical Engineering building to the new Birck Nanotechnology Center on campus. Consequently, limited progress has been made toward the fabrication of diodes. Devices are currently awaiting deposition of a 1 μm thick poly-Si layer which will serve as an mask for the device termination implant.

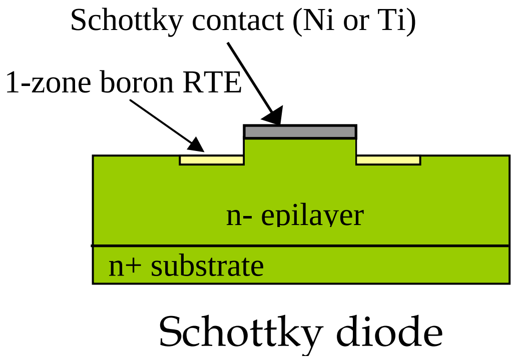

Figure 1. SiC Schottky diode with a 10 μm thick epilayer and an n-type doping of $5x10^{15}$ cm^{-3}.

In addition to the device processing activity, considerable progress is being made in the modelling of SiC devices using *Medici* simulations. Simulations were performed on SiC PiN and Schottky diodes with drift layer thicknesses of 10 μm and a doping of 3×10^{15} cm^{-3}. The structure simulated are very similar to the device shown in Fig. 1, except that the PiN diode has a 1 μm thick p-type epilayer between the n- drift layer and the anode contact. The expected breakdown voltage for the devices is near 1600 V with an expected voltage rating for service of about 1000 V. Figures 2 and 3 show the forward bias characteristics for the PiN and Schottky diodes respectively as temperature is varied.

During this research, it was found that device results were very sensitive to the doping of the termination region. To obtain the results in Figs. 2 and 3, much work was done to determine the correct doping of the device termination region. The issue had to do with the electric field dependence on the doping of the termination. Initial simulation runs were performed with a termination doping of 1×10^{17} cm^{-3} p-type. This was found to be much too high because the Schottky was behaving similar to the PiN diode. A series of simulations was then performed at a temperature of 300K on the Schottky diode to investigate how the doping of the termination region effected the forward characteristics. Simulations with termination doping ranging from 1×10^{16} cm^{-3} to 1×10^{14} cm^{-3} were done. It was found that the appropriate doping for the termination was 1×10^{14} cm^{-3} p-type.

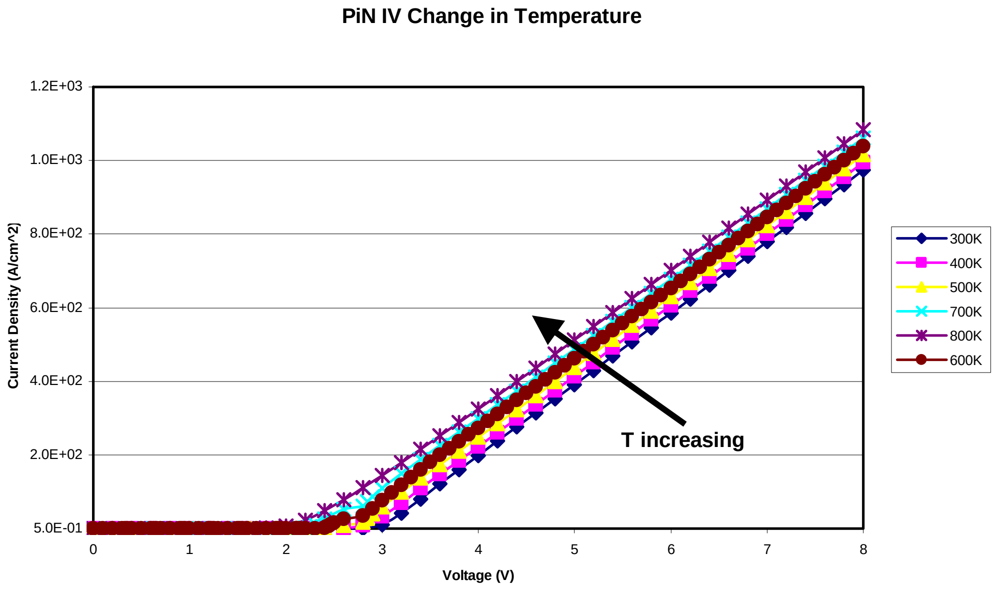

Fig. 2 Forward bias characteristics for SiC PiN diodes as a function of temperature.

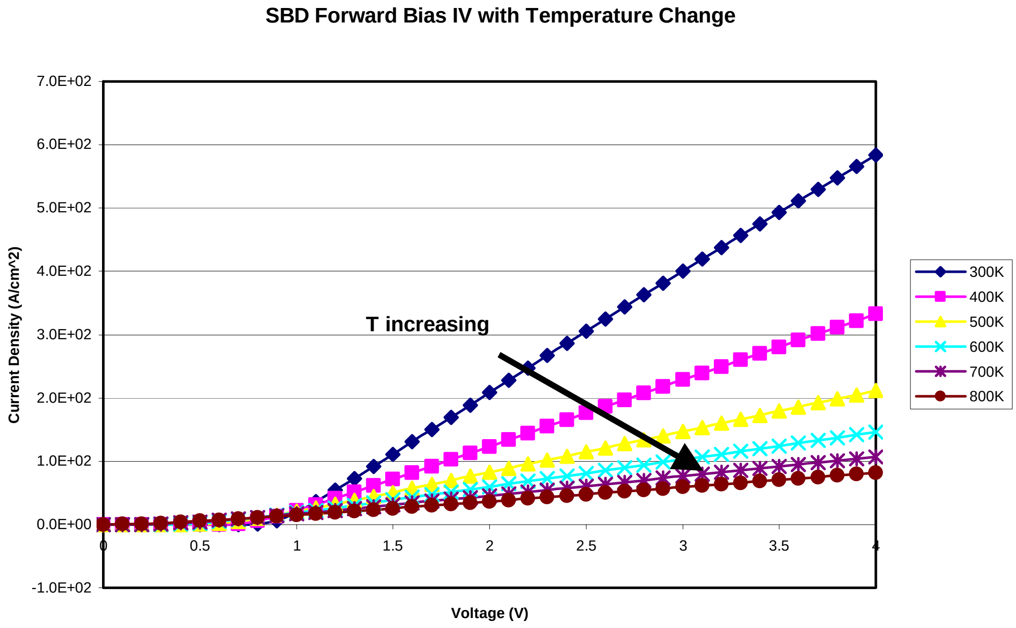

Fig. 3 Forward bias characteristics for SiC Schottky diode as a function of temperature.

The characteristics of Figs. 2 and 3 can be explained straightforwardly. The resistance of the drift layer in the Schottky diode is dependent on the electron mobility. As temperature increases, phonon scattering of carriers increases causing the resistance to increase. In Fig. 3, the decreasing slope of the forward characteristics as temperature increases is dramatically evident. This is due to reduced carrier mobility.

As for the PiN diode, the resistance of the drift region not only depends on electron mobility, it is sensitive to conductivity modulation. Conductivity modulation in turn, depends on the minority carrier lifetime. Minority carrier lifetime increases as temperature increases, causing a slight decrease in drift region resistivity as temperature increases. This is evident in Fig. 2 as higher temperatures correlate to slightly higher currents in the figure.

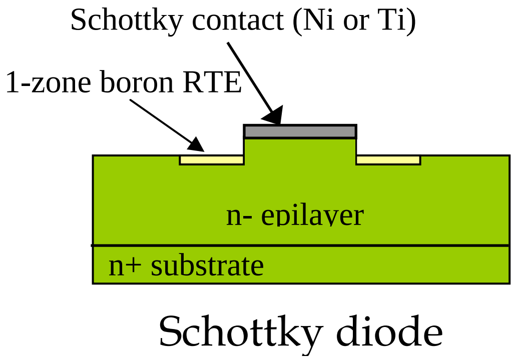

Figure 1. Cross-section of SiC Schottky diode.

Task 2. Optimal Efficiency Motor Control Strategies
Marian Kazimierczuk, Wright State University

Validation of Equations for Conduction Losses in Silicon Carbide Diode Used in Pulse-width Modulated (PWM) Buck Converter

Equations for conduction losses in Silicon Carbide (SiC) diodes applied in pulse-width modulated (PWM) converters, used in switching-mode power supplies. A buck PWM hard-switching converter was designed. Simulations of this converter were performed using PSPICE to obtain the waveforms for transient and steady-state operation. The SiC diode current waveform iD(t) and the diode voltage waveform vD(t) were obtained. The product of these waveforms pD(t) = iD(t)vD(t) is the instantaneous power loss in the diode. The average value of the diode instantaneous power is the diode power loss. The average diode power loss was obtained from the simulations. The results calculated from the analytical equations derived in the previous quarter and obtained the simulations in this quarter were compared. The major difficulties in simulations of power circuits with SiC p-n and Schottky diodes are in obtaining the SPICE model parameters. The main difficulty in estimating the SiC diode power loss is the estimation of the p-n and Schottky diode turn-off power loss.

Task 3 Islanding and Distributed Generation for Enhanced Electric Power Grid Security
Faculty:
Shripad T. Revankar, Nuclear Engineering, Purdue University
Mitch Wolff, Mechanical Engineering, Wright State University
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

Tasks Completed:

1.) We have completed a SIMULINK model of a combustor. The combustor will be used to prepare the gas entering the cathode of a molten carbonate fuel cell by oxidizing the anode exhaust with air. Assumptions imposed are that gas mixtures are ideal and chemical reactions are complete and prompt given a minimum theoretical air supply.

Also, the combustion chamber is a continuously well stirred adiabatic tank. With this in mind the combustible compounds CH_4, CO, and H_2 leaving the anode are fully oxidized in the combustor and gas mixture temperature found using temperature dependent specific heats.

2.) An investigation of model equations for steady state and dynamic MCFC/SOFC calculations has been performed. Some of the basic equations can be seen in Appendix A. Also, an estimation of a sub-megawatt plant states has been made using information from literature. This can also be seen in Appendix A.

3.) Implementation of the equations in SIMULINK for a steady state solution of MCFC has lead to a nearly complete model. Anode and Cathode steady state mass balance has been completed and verified for constant temperature and pressure. Energy balance model has been written and implemented with constant pressure. A comparison of the steady state results obtained at constant pressures to those found in literature can be seen in Table 1.

4.) We have been working on the transient SIMULINK turbine model and the Fully Automated Digital Engine Control (FADEC) system to make it compatible with the hybrid system. The model is being scaled up from the ~30kW to the sub-megawatt plant size.

Table 1: Comparison of steady state data. Letters and numbers are state points in Figure 1.

	Simulations							
Mole Fraction	[1]	[A]	[2]	[B]	[3]	[C]	[4]	[D]
H_2	0.1168	0.1168	0.0000	0.0000	0.0741	0.0735	0.0000	0.0000
CH_4	0.2798	0.2798	0.0000	0.0000	0.0011	0.0011	0.0000	0.0000
CO	0.0005	0.0005	0.0000	0.0000	0.0462	0.0464	0.0000	0.0000
CO_2	0.0346	0.0346	0.1553	0.1553	0.4533	0.4532	0.0476	0.0476
H_2O	0.5662	0.5662	0.1553	0.1553	0.4245	0.4249	0.1880	0.1880
N_2	0.0000	0.0000	0.5590	0.5590	0.0000	0.0000	0.6778	0.6778
O_2	0.0000	0.0000	0.1294	0.1294	0.0000	0.0000	0.0865	0.0866
Temp(K)	849	849	838	838	950	954	950	954
Molar Flow (mol/s)	17.61	17.61	140.93	140.93	43.73	43.73	116.41	116.41

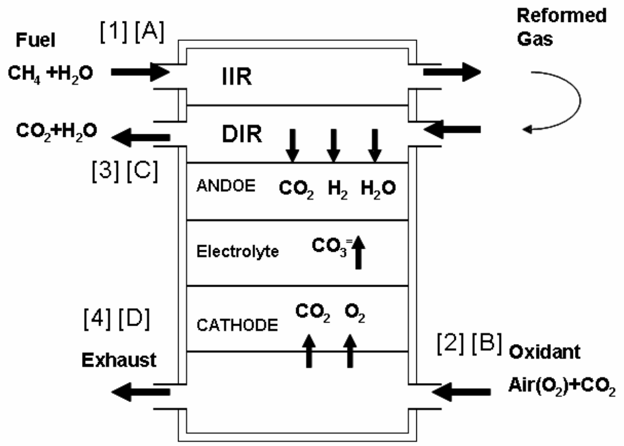

Fig. 1. MCFC stack diagram

Plans for Next Quarter:

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

Michael Capano, Purdue University

When this progress report was written, the reverse bias characteristics were not yet completed. Next quarter, we expect to present more results on simulations of SiC diodes. Specific variables of interest are to look at how SiC materials parameters influence device simulations. Additionally, power dissipation studies will begin. We anticipate further progress in the fabrication of devices in support of this program.

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

Shripad T. Revankar, Nuclear Engineering, Purdue University
Mitch Wolff, Mechanical Engineering, Wright State University

The following efforts are planned for the next quarter:

1) Steady State Model for the MCFC/GT and SOFC/GT hybrid system (continued)
2) Transient Model for the MCFC/GT and SOFC/GT hybrid system with SIMULINK (continued)
3) Incorporation of the transient/control models for turbine (continued)
4) Evaluate transient model and control systems for turbine