

(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 part 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 this task 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:

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:

The SiC Schottky diode being modeled in *Medici* is shown in Fig. 1. A general cross-section was reported last quarter. Omitted in that report were dimensions for the device. Dimensions are included here. The lightly n-type doped epilayer is 10 μm thick, on a heavily-doped substrate that is represented as only 4 μm thick. The total width of the device is 300 μm . The backside ohmic contact runs the entire width of the device along the bottom edge of the substrate (i.e. at $y = 14.0 \mu\text{m}$; y measured downwards from top left corner). Contacts have no dimension within the *Medici* model, only contact resistance values. The termination region, denoted in yellow, starts at $x = 150 \mu\text{m}$ and ends at $x = 200 \mu\text{m}$, for a total width of 50 μm . (x is measured from top left corner). The top Schottky contact extends from $x = 0$ to $x = 150 \mu\text{m}$, for a total width of 150 μm .

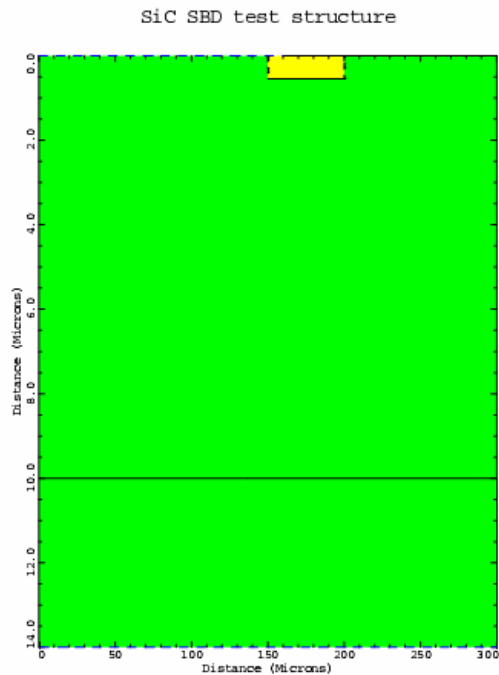


Fig. 1. Cross section of SiC Schottky diode as modeled in *Medici*.

Research involving device simulation using *Medici* dealt with two aspects of diode analysis. First is the accurate representation of conductivity modulation in PiN diodes. PiN diodes are bipolar devices with current being carried by both majority (electrons) and minority (holes) carriers. As such, under high-level injection conditions, the current-voltage characteristic should not display a simple resistive (linear) characteristic for the PiN that is displayed for the Schottky diode. Yet, some PiN simulations did show a linear forward I-V characteristic. This was found to be related to the contact resistance. Figure 2 illustrates contact resistance effects by varying the contact resistance from 5×10^{-4} ohms (blue curve) to 5×10^{-5} ohms (magenta curve). The comparison shows that an excessively high series resistance can eliminate the benefits of conductivity modulation. Future simulations are performed using the lower contact resistance. This lower resistance has been achieved in practice.

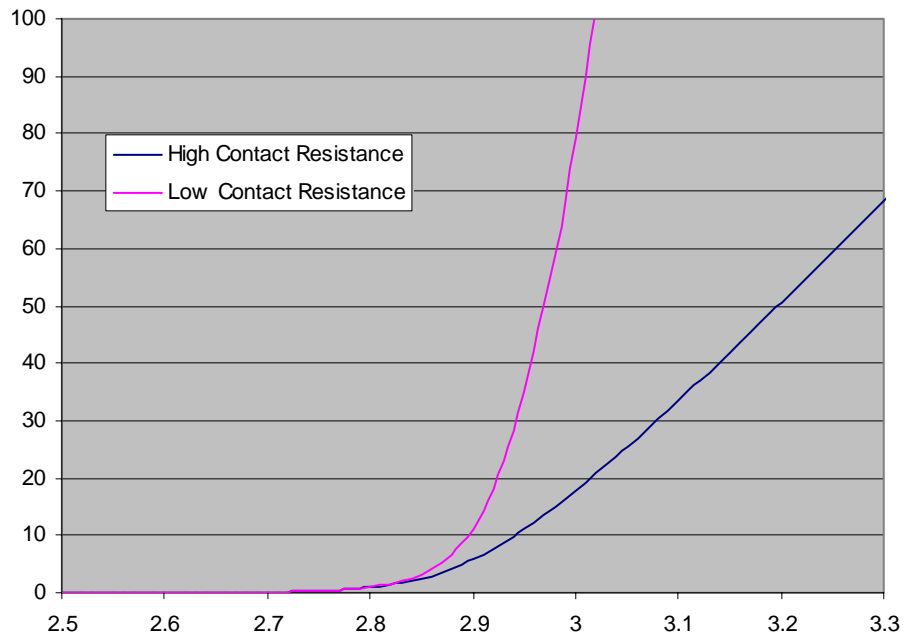
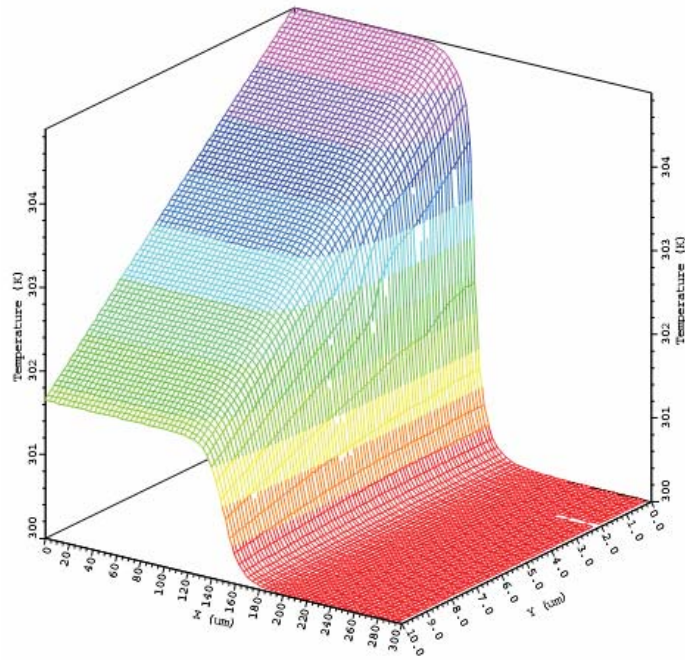


Fig. 2. Current(y)-voltage(x) characteristic for PiN diodes with different ohmic contact resistance.

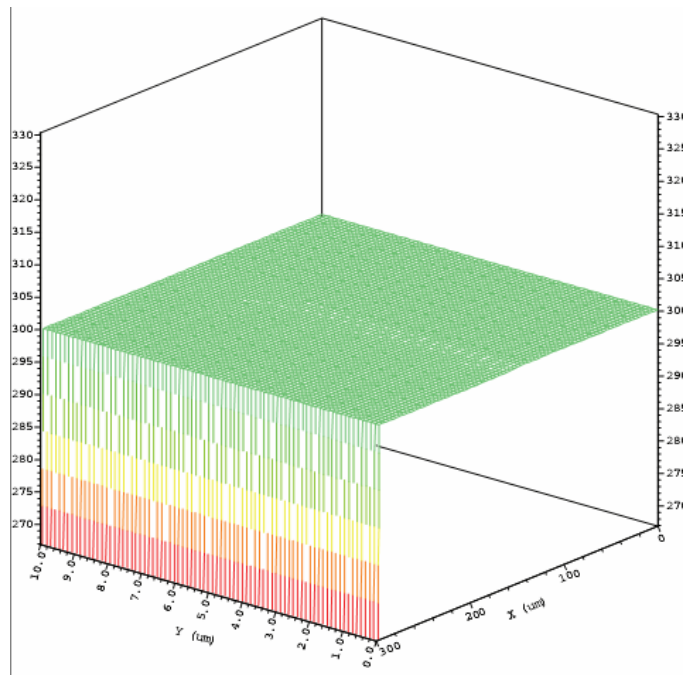
One major aspect of the PiN/Schottky comparison is the influence of temperature on the I-V characteristics. Using the Lattice-Temperature Advanced Application Module in *Medici*, simulations have been performed which include a solution of the heat equation,

$$\rho c \frac{\partial T}{\partial t} = H + \vec{\nabla}(\lambda(T)\vec{\nabla}T)$$

A comparison of temperature excursions during forward bias are shown in Fig. 3, the output from *Medici*. Both devices are operated nominally at 300 K. The PiN is shown to have a 5° increase in temperature close to the p-type anode (i.e. $0 < x < 150 \text{ m}$; $y=0$).



(a)



(b)

Fig 3. Temperature variation as function of position in (a) PiN and (b) Schottky diodes.

A negligible temperature increase is seen in the Schottky diode due to the absence of minority carriers. Similar temperature comparisons for reverse biasing are currently being performed and should be reported next quarter.

Plans for Next Quarter:

The intention for the next quarter is to finish the *Medici* comparison of SiC Schottky and PiN diodes rated for 1500 V operation. Also, the completion of Schottky diode fabrication will be reported.

Task 2. Optimal Efficiency Motor Control Strategies

Marian Kazimierczuk, Wright State University

Objectives:

The objective of this part of the project is to design a dc/ac 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 rectifiers and clamp circuits in dc/dc power converters and power-factor correctors [2]. The use of these 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.

Publications:

The following conference papers have been submitted:

- [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:

Models of power MOSFETs and power diodes were developed. The expressions of the rms currents through the power MOSFETs, power diodes, an inductor, and a capacitor were derived. Using the models of the power devices and their rms currents, the expressions for the conduction power losses and the switching power losses were derived. Using the losses, an expression for the efficiency of the dc/dc inverter is derived. An expression for the gate-drive power of each transistor is also derived. The losses in silicon carbide (SiC) and silicon (Si) power devices are calculated and compared at the switching frequency equal to the resonant frequency.

Plans for Next Quarter:

The performance of the dc/dc inverter will be investigated below and above resonance. Expressions for the rms current in power MOSFETs and power diodes will be derived. Next,

expressions for power losses and the efficiency of the dc/dc inverter will be derived for operation above and below resonance.

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

Academic Faculty:

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Mitch Wolff, Professor, Department of Mechanical Engineering, WSU

Graduate Students:

Brian Wolf

M.S. Candidate Nuclear Engineering, PU

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Objective:

The objective of this task is to investigate the control and performance of distributed generation during islanding of an electric power grid. A high temperature fuel cell coupled to a gas turbine, a hybrid system, 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.

Research Progress:

In the past quarter a complete explicit dynamic model of a MCFC has been developed which includes specific controls to the fuel cell system. The model was implemented using SIMULINK software and simulation of a plant trip, in which the fuel cell load starts at steady state and abruptly goes to zero has been performed. The steady state and dynamic behavior has been benchmarked with model results in the literature (Lukas et al. 1999). The model uses differential equations to calculate mass fractions, pressure, and temperature with basic simplifying assumptions. Also a dynamic model of an oxidizer has been developed and implemented to the fuel cell system. The oxidizer assumes that reactions taking place are complete and spontaneous given a minimum amount of theoretical air needed for oxidation. A Generic Microturbine Generator that will be coupled with the fuel cell has been developed with the following components modeled in Matlab/Simulink: Centrifugal Compressor, Radial Inflow Turbine, Turbine Diffuser, Combustion Chamber, and Primary Surface Recuperator. A counter-flow double-pipe heat exchanger SIMULINK model has been completed which calculates the pressure drops and outlet temperatures of the hot and cold fluids for a given set of inlet temperatures and mass flow rates. Contacts between Wright State University and Purdue University personnel working on this collaborative project have been established. A meeting was held at Purdue University to discuss the linkage between the fuel cell and the turbine models. Direct linking of the turbine models with the fuel cell models to create a complete dynamic fuel

cell/ turbine hybrid system is under progress. Linking the models will mainly consist of optimizing the heat transfer between components by heat exchangers and developing hybrid system controls.

Plans for Next Quarter:

In the next quarter, a complete dynamic hybrid system linking the fuel cell to the turbine should be completed. Control systems and balance of plant will be included in the dynamic model. Also, work has been started on a Solid Oxide Fuel Cell model.

References:

Lukas, M. D., Lee, K. Y., & Ghezal-Ayagh, H. (1999). Development of a stack simulation model for control study on direct reforming molten carbonate fuel cell power plant. *IEEE Transaction on Energy Conversion*, 14(4), 1651-1657.