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Semiconductor Power-Device Modeling

Task 2 Report: Technical, Strategic, and Market Issues

Prepared for

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RTI Project Number 7007-02

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1 Introduction

Research Triangle Institute is conducting a microeconomics impact assessment of the National Institute of Standards and Technology's (NIST's) contributions to the insulated-gate bipolar transistor (IGBT) power-device industry. The main focus of the impact assessment is to estimate the social returns from NIST's investments in mathematical modeling capabilities. The study involves both retrospective and prospective analyses of NIST's contributions to date on existing products employing IGBTs. In addition, the study includes a qualitative assessment of NIST's impact on future products employing IGBTs, such as electric cars and advanced medical applications.

Our approach to estimating NIST's contribution to the semiconductor power industry requires two main steps. First, we identify the impact associated with the mathematical modeling of IGBTs. This step includes estimating benefits associated with currently affected markets and projecting potential impacts of existing modeling capabilities into the near future. Second, we assess NIST's impact on developing and adopting mathematical modeling of IGBTs. NIST's contribution to social welfare is then a portion of the estimated total net benefit to society from mathematical modeling of IGBTs.

In this report we describe the institutional setting for the technology and determine the technical impacts of advances in power-device modeling on the affected markets. Section 2 identifies and characterizes technology trends and applications for semiconductor power devices and Section 3 profiles the key industries affected. Technical impacts of mathematical modeling and the barriers to the adoption of mathematical modeling in IGBT design are presented in Sections 4 and 5, respectively. Section 6 discusses NIST's contribution to mathematical modeling and its impacts on the economy

2 Technology Characteristics, Trends, and Applications

In 1948, American physicists John Bardeen, Walter H. Brattain, and William Shockley of Bell Telephone Laboratories invented the transistor, a device at the heart of modern power electronics. The transistor is a small electronic unit consisting of semiconductor materials (impure germanium and silicon) used as a voltage and current amplifier in electrical machinery and equipment. Nearly 50 years after its invention, the bipolar transistor has developed to such an extent that millions of transistors can occupy a fingernail-sized sliver of silicon (Baliga, 1997).

A transistor is designed to operate switches and block or permit the flow of electric current. Transistors are distinguished by the amount of power they control, which is determined, in turn, by the individual unit's maximum operating voltage and current handling capability. When the transistor is switched on, either with voltage or current depending on the type, electric current is allowed to pass through the device. When the transistor is switched off, electric current is blocked from coursing through the transistor. At the same time, the transistor maintains its support of the voltage on the wire.

Soon after its discovery at Bell Labs, engineers began to apply the transistor technology to all forms of electric devices. Two trends quickly developed: one towards miniaturization, the other towards the grandiose (Baliga, 1997). For products ranging from radios to the earliest computers, the transistor was shrunk to fit in all manners of microapplications, ushering in the age of electronics. For other applications, the transistor was enlarged and built to withstand and conduct massive amounts of power on command for generators and in power conditioners.

The complementary metal oxide semiconductor (CMOS) was an improvement on the bipolar transistor and was developed in the early 1970s. The introduction of the CMOS allowed greater power gain and control, but it was subject to destructive failures, necessitating the use of protective circuits. CMOSs were originally developed for microelectronic applications but have since become the basic building block of silicon integrated circuits.

A descendant of the CMOS, the metal oxide semiconductor field effect transistor (MOSFET) switches on and off faster and does not require the cumbersome protection circuits that bipolar transistors need. It switches on and off with voltage, not current. Current flow is limited to short bursts whenever the MOSFET is turned off or on. Although the MOSFET's ability to manage low voltages is well documented, its current-handling capability is less effective when operated at more than 100 volts. MOSFETs are found in consumer electronics, personal computers, automotive systems, and other low-power applications; it is currently known as the every-day transistor.

In the late 1970s, experiments with MOSFET/bipolar transistor combinations led to MOSFETs that could be used to control a bipolar transistor. These devices can be switched by a small voltage, while still operating at high amperes. This discovery, known as a MOS-gated thyristor, led to RCA's 1982 discovery of the IGBT. IGBT semiconductors are about the size of a postage stamp and can be grouped together to switch up to 1,000 amperes of electric current at voltages of up to several thousand volts.

Currently power electronics devices control an estimated 50 to 60 percent of the electric power generated in developed countries (Baliga, 1997). They are used in products as varied as car ignitions, electric bullet trains, blenders, fluorescent light ballasts, and computers. Table 2-1 presents the power transistor market by device type. The remainder of this report focuses on IGBT applications and markets.

Table 2-1. North American Power Transistor Market: 1993

Product	Revenues %
Bipolar	60
MOSFET	30
IGBT	10

Source: Profound. 1997. "North American Power Semiconductor Markets—Introduction, Total Market, Power Transistor, and Rectifier Market." <http://www.profound.com/htbin/>.

2.1 TECHNICAL CHARACTERISTICS OF IGBTS

The IGBT is a hybrid of two transistors: the bipolar transistor and the MOSFET. The simple bipolar transistor consists of three layers: the top (the emitter), the middle (the base), and the bottom (the collector). The three layers alternate conductivity type. The areas between the conductivity types are called p-n junctions. Electrons pass through these junctions to move from one layer to another. If the electric potential or voltage on the segments is properly determined, a small current between the emitter and base connections generates a large current between the emitter and collector connections, thereby producing current and amplification (Columbia Encyclopedia, 1998).

Base bipolar transistors and MOSFETs are the two types of transistors used in IGBTs. Bipolar transistors are simple in design and rugged in performance. They effectively control large amounts of power and can be switched at high speeds. The main drawback, however, is that the amount of power they consume is directly related to the amount of power they control and conduct. In other words, bipolar transistors require a large current flow to control a larger current (Baliga, 1997).

The base bipolar transistor used in IGBTs is the p-n-p transistor. This transistor is the inverse of the standard n-p-n bipolar. The standard bipolar has a narrow base region and a lightly doped, thick collector. In contrast, the IGBT's base is thick and lightly doped and the collector is thin and highly doped. The advantage of the transistor's inverse properties is that they enable it to support high voltages across its output terminals, emitter, and collector when it is turned off. This had been previously accomplished by making the collector thick and lightly doped, but in an IGBT this is accomplished using thinner layers (Baliga, 1997).

MOSFETs are the other type of transistor used in IGBTs. MOSFETs evolved from the CMOS that had been developed during the 1970s for microelectronics. The n-p-n MOSFET, or n-channel MOSFET, has two n-type regions, the source and drain, that play the same roles as the collector and emitter in the bipolar transistor. The base in the MOSFET is known as the substrate, the p-type region. The top of the substrate is a metal gate that allows an electrical field to be created in the substrate when a positive voltage is applied to it. The field forces positively charged holes (electron deficiencies) from the substrate through the gate while attracting electrons toward the substrate surface. The moving electrons allow the current to flow through the substrate. From the perspective of an IGBT, the key attribute of the MOSFET is that it is switched on and off with voltage, not current.

MOSFETs cannot control large amounts of power, but they can be switched on and off at incredibly high speeds. In addition, they do not require the protective circuits of their predecessor, the CMOS. The main limitation of MOSFETs is in their ability to efficiently handle high-voltage currents. As a MOSFET controls voltages of 100 volts or more, it loses its ability to control that power efficiently.

The inefficiency of MOSFETs at high power led to the development of the IGBT for control of medium-power devices in the 1980s. In an IGBT, the MOSFET provides the control current to the bipolar transistor. To create an IGBT, the bipolar transistor and the MOSFET are joined so that the channel current flowing in the substrate of the MOSFET is also the current that is applied to the base of the bipolar transistor. The technical advantages from joining these two devices are three-fold (Baliga, 1997). First, the IGBT's MOSFET is typically controlled by 10 volts, but the whole unit can control nearly 1,500 volts and 100 amperes. This equates to a possible power gain of 10 million or more. The high power gain allows the unit to be controlled by delicate integrated circuits but require the use of protective circuits to prevent destructive failure.

Second, the IGBT has a higher operating current density than its components. The electrical current flowing through the IGBT's MOSFET is the control current for the bipolar transistor. The bipolar transistor's emitter-collector current joins the MOSFET's channel current to produce the IGBT's total output current. The two currents from the IGBT's components are equal; therefore, the IGBT's output current is double that of either of its components.

Third, when switched on, the IGBT has very low electrical resistance between the collector and the emitter. Because so many electrons and holes flow through the bipolar's base region from the emitter and collector, the base's conductivity increases 1,000 times. The improved conductivity keeps power loss at a minimum, especially when compared to the MOSFET and bipolar transistor alone. These three attributes allow IGBTs to be smaller, more efficient, and less expensive to produce for the manufacturer.

2.2 CURRENT APPLICATIONS

IGBTs can be found in a wide range of devices and dominate the 200 to 1,500 volts range. Most of the benefits highlighted in the previous section transfer directly into enhanced performance for products employing IGBTs.

IGBTs switch at a higher frequency than most power electronic devices. Because these high frequencies exceed humans' detection range, the applications employing IGBTs are quieter. Also, the smoother sine wave keeps the motor controlled by the IGBT from generating excessive harmonics. Harmonics create heat and waste energy and can also lead to significant damage to the device and power quality problems.

Applications for IGBTs are concentrated in the automotive, aerospace, HVAC, and power supply markets. IGBTs control a large array of products. In the average household in a developed country, there are 40 electric motors in everything from blenders to compressors (Baliga, 1997). The number of those devices controlled by IGBTs will increase as their usage spreads into smaller devices. IGBTs are used in electric cars, motor-driven machines and equipment, and Japan's Shinkansen bullet trains. General Motors used IGBTs in their machinery at the company's Saturn plant in Tennessee. IGBTs are used in laptop computer manufacturers to rapidly turn images on and off, and in office telephone networks and HVAC applications.

Environmental concerns have placed efficient power control systems high on the list of priorities for manufacturers and regulators alike. The use of IGBTs enables more efficient control of electrical power. The efficient use of electricity through adjustable speed drives (ASD) reduces dependency on and use of fossil fuels. The IGBT is the key component in industrial ASDs. IGBTs also increase the efficiency of HVAC equipment, motor-driven machinery, and electric transport such as cars, streetcars, and trains. IGBTs also allow more precise control of an array of equipment from x-ray machines to robots, saving on energy costs, and thereby bettering the environment (Baliga, 1997).

IGBTs lead to cost reductions for most manufacturers and end users. The use of IGBTs reduces the number of components used, resulting in a reduction of the dimensions and weight of typical converter boxes by about 20 to 30 percent (Et-Info, 1997). The IGBT's smaller size also lowers integration costs, and reduces complexity and increases reliability of the component.

2.3 FUTURE APPLICATIONS AND TRENDS

The growth in IGBT usage in the medium-power control market is expected to continue; no substitute products is anticipated in the foreseeable future. The IGBT currently dominates the market for medium-power control devices between 200 and 1,500 volts. The MOSFET's dominance of the low-power market (100 volts or less) are also not expected to decline because of its relatively low cost.

For large-power control devices (greater than 3,000 volts), the thyristor continues to be the dominant device. Thyristors are capable of controlling high voltage levels on the order of 6,000 volts or more and can carry 1,000 amperes. Even though they are relatively small devices, they require huge control circuits, have slower switching capabilities, and are much noisier. Some Japanese corporations are experimenting with high-voltage applications using groups of IGBTs. Table 2-2 presents future applications for IGBTs.

Table 2-2. Projected Smart Power Technology Applications by the Year 2000

Application	Projected Market
Display drives	$2 billion
Computer power supplies	$3 billion
Adjustable speed drives	$1 billion
Factor automation	$1 billion
Telecommunications	$5 billion
Appliance controls	$3 billion
Consumer electronics	$2 billion
Lighting ballasts	$3 billion
Smart homes	$5 billion
Air-craft electronics	$5 billion
Automobile electronics	$10 billion

2.4 SIMULATION MODELS FOR IGBTS

The simulation modeling of power electronics devices has had a significant impact on the design process for products employing IGBTs. Modeling allows engineers to determine the best design characteristics before physical prototypes are produced, saving both time and money. The simulation models developed and applied vary greatly in nature and may be physics-based, analytical, numerical, or empirical (Powell, 1997). A model can determine the range of a device and allow an engineer to explore alternatives in a more timely and efficient manner than if (s)he had produced a physical prototype.

Interviews conducted by RTI with industry experts have confirmed the importance of modeling IGBTs. Software companies that provide modeling software applications attest to IGBTs' increased use among the various industries that design and manufacture system devices. A detailed discussion of the IGBT system design process and the impact of simulation modeling is presented in Section 4.

3 Characterize Key Industries and Institutions

In this section we identify and describe the markets likely to be affected by mathematical modeling of IGBT devices. The primary market structure characteristics included in our analysis are the number of sellers and buyers, product differentiation, vertical integration, and horizontal integration of these markets. Our analysis focuses on three tiers of the supply chain for products employing IGBTs: software companies, device manufacturers, and application manufacturers.

3.1 SOFTWARE COMPANIES

MicroSim Corporation and Analogy Incorporated are the two major companies in the U.S. producing modeling software for power electronics applications. These two companies' software products support virtually all the simulation modeling of IGBTs (Benjakowski, 1997). The only known foreign competitor that produces IGBT modeling software is in Switzerland. The University of Zurich produces a modeling software package that has been used in IGBT design (Clemente, 1997).

MicroSim recently announced the completion of a merger with Orcad Incorporated, a leading supplier of electronic design automation (EDA) software and services to engineering firms developing products on the Intel/Microsoft platform (OrCAD, 1998). Based on recent company 10-KSB filings, OrCAD reported $20.9 million in revenue and 123 employees for 1996 (OrCAD, 1997). The companies' combined revenues for the first 9 months of 1997 were $31 million (OrCAD, 1998). MicroSim has incorporated NIST's mathematical modeling algorithms in its software product PSPICE. PSPICE was developed through the combined efforts of MicroSim, NIST, SRC, and University of Florida (Shen, 1997).

Analogy, like MicroSim, is also a relatively small company in terms of sales and employment. As of March 1997, the company reported $24 million in revenue and 181 employees (Analogy, 1997). Analogy worked directly with NIST to include mathematical modeling in the development of SABRE. SABRE is generally viewed by device application manufacturers as a more accurate modeling tool, but it is more costly to use (Benjakowski, 1997).

3.2 DEVICE MANUFACTURERS

U.S. manufacturers have focused on IGBT devices with current capacities from 10 to 50 amperes. These devices employ a single silicon chip. Table 3-1 provides information on several U.S. manufacturers of IGBT devices. Detailed company information was available for four of the five companies based on filings with the U.S. Security Exchange Commission. Additional sales, employment, and end-use application data were obtained from Information Access Corporation (1998) and company World Wide Web sites.

Advanced Power Technology (APT) was formerly owned by Sunstrand Corporation. Although APT is no longer controlled by this company, its power switches continue to be used in Sundstrand's variable speed constant frequency (VSCF) power converters for aircraft (APT, 1996). As shown in Table 3-1, APT devices can be used in a variety of other applications, including automobile electronics, consumer audio systems, factory automation, and computers and telecommunications. The APT market can be considered horizontally integrated because it manufactures power semiconductor products and sells them directly to other manufacturers that are not part of their corporate structure.

Table 3-1. Company-Level Data for U.S. Manufacturers of IGBT Devices

Name	Parent Company	Organiz-ation Type	Sales ($million)	Employment	Fiscal Year Ended	End-Use Applications
Advanced Power Technology	—	NA	NA	NA	NA	Automotive electronics, consumer audio systems, factory automation, computers and telecommunications uninteruptible power supplies, sonar and radar systems
Delco Electronics	General Motors Corporation	Public Subsidiary	$5,560.00	31,000	12/31/95	Automotive electronics for General Motors automobiles
Harris Semiconductor	Harris Corporation	Public Subsidiary	$637.60	8,489	06/30/95	Motor controllers and power supplies, automotive electronic systems, communications systems, military and aerospace applications
International Rectifier	—	Public	$486.10	4,385	06/30/97	Automobile electronic systems, computer applications, consumer electronics, lighting applications, industrial applications, government and aerospace applications
Motorola Incorporated	—	Public	$27,973.00	139,000	12/31/95	Communications, automotive, industrial, consumer electronics and computer applications

NA = Not available.

Sources: Information Access Corporation. 1998. Business Index [computer file]. Foster City, CA: Information Access Corporation.

Advanced Power Technology (APT). World Wide Web Site: <http://www.advancedpower.com/Co_Over/BackeG_96.html. Last Updated December 16, 1996.

General Motors Corporation. March 20, 1997. 10-K for year ended December 31, 1996. EDGAR Database: <http://www.edgar-online.com/pointcast/gdoc/?choice=2-616283&nad=0>. Bethesda, MD: Lexis/Nexis.

Harris Corporation. August 29, 1997. 10-K405 for year ended June 27, 1997. EDGAR Database: <http://www.sec.gov/Archives/edgar/ data/202058/0000950152-97-006326.txt>. Bethesda, MD: Lexis/Nexis.

International Rectifier Corporation. September 26, 1997. 10-K405 for year ended June 30, 1997. EDGAR Database: <http://www.sec.gov/ Archives/edgar/data/316793/0000912057-97-031847.txt>. Bethesda, MD: Lexis/Nexis.

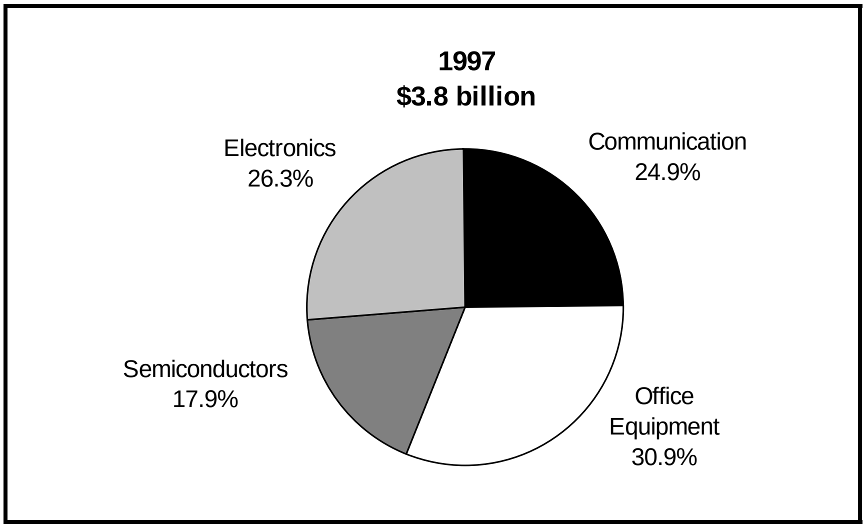
Motorola Incorporated. March 31, 1997. 10-K/A for year ended December 31, 1996. EDGAR Database: <http://www.sec.gov/ Archives/edgar/data/68505/0000950131-97-003500.txt>. Bethesda, MD: Lexis/Nexis.

Delco Electronics, a subsidiary of General Motors, manufactures IGBT devices that are used in the electrical systems of GM automobiles. Delco devices are included in GM automobile systems such as antilock brakes and traction controllers, air bag deployment, and audio and security systems. In the automobile industry, many firms are vertically integrated—they own a variety of subsidiaries that manufacture various components of automobiles. Delco Electronic's production of IGBT devices is one component of GM's vertical production structure.

Harris Semiconductor, a subsidiary of Harris Corporation, produces custom-integrated circuits and discreet devices that are used in a variety of products such as automotive systems, wireless communications, telecommunications, video and imaging systems, multimedia, industrial equipment, computer peripherals, and military and aerospace systems. As shown in Figure 3-1, semiconductor sales accounted for 18 percent of Harris Corporation's total revenues in 1997 (Harris, 1997). Harris Corporation's communications segment (24.9 percent), office equipment segment (30.9 percent), and electronics segment (26.3 percent) accounted for the majority of the company's revenues. The Harris Corporation is vertically integrated to the extent that its communications equipment, office business equipment, and electronic systems incorporate IGBTs produced by Harris Semiconductor. However, unlike Delco Electronics, Harris Semiconductor's customers also include other original equipment manufacturing firms, and these customers are not restricted to the automobile industry.

International Rectifier is a worldwide supplier of power semiconductors and a leader in the power MOSFET segment. The company's devices are incorporated in subsystems and end products manufactured by other companies that are not part of its corporate structure. As shown in Figure 3-2, the company's power MOSFET products and IGBT transistors accounted for approximately 70 percent of fiscal 1997 sales. The remaining 30 percent resulted from sales of high voltage control ICs, high-performance diodes, and high-power rectifiers and thyristors. International Rectifier's major customers are listed below by industry segment, and the company reported that no single

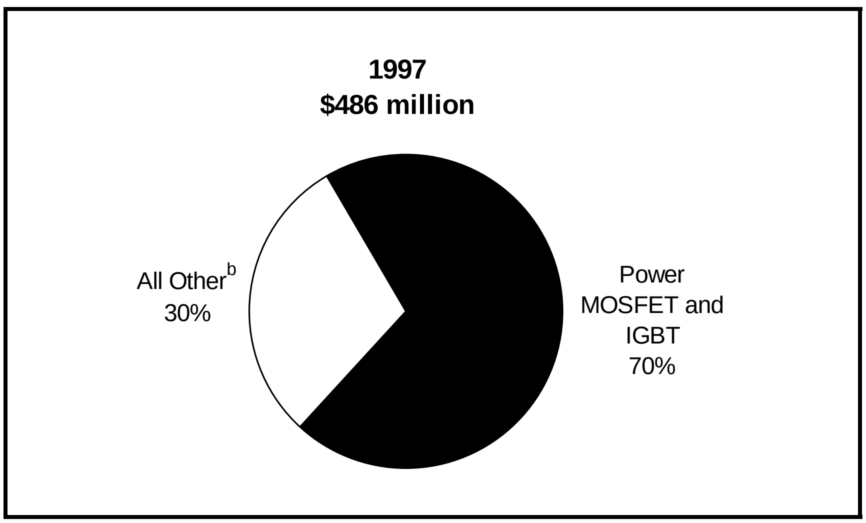
Figure 3-1. Distribution of Harris Corporation Sales by Segment: 1997[a]



[a]Fiscal year ended June 27, 1997.

Source: Harris Corporation. August 29, 1997. 10-K405 for year ended June 27, 1997. EDGAR database: <http://www.sec.gov/Archives/edgar/data/202038/0000950152-97-006326.txt>. Bethesda, MD: Lexis/Nexis.

Figure 3-2. Distribution of International Rectifier Sales by Product: 1997[a]



[a]Fiscal year ended June 30, 1997.

[b]All other including high-power voltage controls, diodes, rectifiers, and thyristors.

Source: International Rectifier Corporation. September 26, 1997. 10-K405 for year ended June 30, 1997. EDGAR database: <http://www.sec.gov/Archives/edgar/data/316793/0000912057-97-031847.txt>. Bethesda, MD: Lexis/Nexis.

customer accounted for more than 10 percent of fiscal 1997 revenues:

- automotive—Delco, Ford, Siemens, and Bosch
- computer segment—IBM, Hewlett Packard, and Compaq
- consumer electronics—Philips and Sony
- telecommunications—Lucent Technologies, Motorola, and Nokia
- industrial applications—Emerson, Sanken Electric, and American Power Conversion
- Distributors—Arrow Electronics, Future Electronics (International Rectifier, 1997)

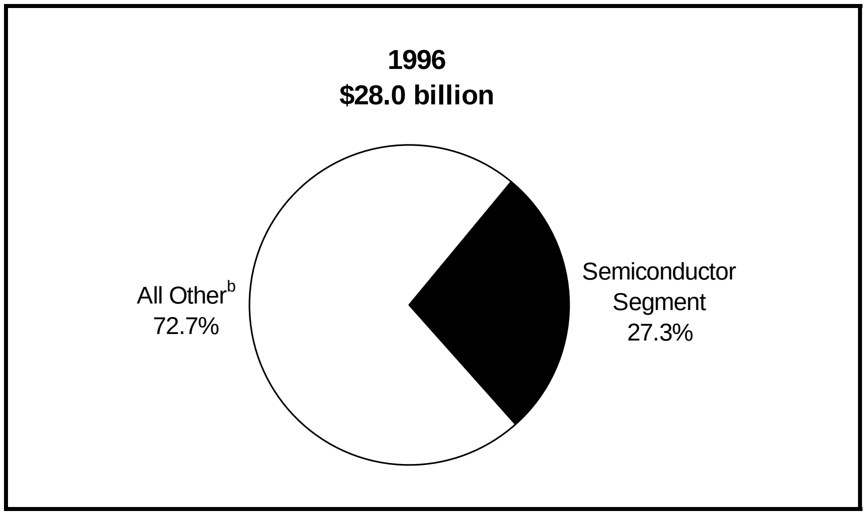
Motorola Corporation's semiconductor segment designs, manufactures, and distributes discrete semiconductors and integrated circuits. Figure 3-3 shows the distribution of Motorola sales by segment. As shown, semiconductor sales accounted for 27 percent of Motorola's total revenue. Motorola produces a wide range of other products that potentially use IGBTs such as cellular phones, portable radios, and modems. Like Harris Corporation, Motorola can be considered vertically integrated to the extent that it incorporates these IGBTs as an input in their production of other products. Motorola sells semiconductors directly to other customers. Communications (33 percent) accounted for the largest share of semiconductor sales to other companies, followed by computer (23 percent), automotive (17 percent), industrial (16 percent), and consumer electronics (11 percent) (Motorola, 1997).

3.2.1 Foreign Device Manufacturers

Japan is the leading foreign country manufacturing IGBT devices. Most Japanese companies focus on devices with high current capacity (200 to 1,000 amperes). Japan is the predominant world supplier of devices within this range. These devices are hybrid in nature; that is, they contain multiple IGBT chips in parallel. For example, an IGBT device with a capacity of 400 amperes may employ three IGBT chips in parallel. The following Japanese firms manufacture IGBTs:

- Fuji Electric
- Mitsubishi Electric
- Hitachi
- Toshiba

Figure 3-3. Distribution of Motorola Sales by Segment: 1997[a]



[a]Fiscal year ended December 31, 1997.

[b]All other segments including general systems, automobile products, message media, and interaction products.

Source: Motorola Incorporated. March 31, 1997. 10-K/A for year ended December 31, 1996. EDGAR database: <http://www.sec.gov/Archives/edgar/data/68505/0000950131-97-003500.txt>. Bethesda, MD: Lexis/Nexis.

3.3 APPLICATION MANUFACTURERS

Power semiconductors are used in a broad range of commercial and industrial applications. Table 3-2 identifies end-use applications and typical products employing MOSFET and IGBT devices.[1] Table 3-2 also indicates the share of the IGBT market for each application. Thirty-six percent of IGBTs produced are used in industrial applications and 30 percent of IGBTs produced are used in computer and communications applications. The following subsections describe some of the largest industry segments that employ IGBTs in their products.

3.3.1 HVAC Compressors

The IGBT is the principle component in ASDs. ASDs' main advantage is that they enable motors to run more efficiently at part loads. IGBTs are also used to build silent compressors for

[1]Detailed market information was not available for IGBTs separately. The MOSFET/IGBT market was approximately $7 billion in 1997 (International Rectifier, 1998). IGBTs accounted for 25 percent of the MOSFET/IGBT market.

Table 3-2. Commercial and Industrial Applications Employing IGBT Devices

Applications	Typical Products	Share of IGBT Market
Computers and Communications	PCs, laptops, disk drives, printers	30%
Automotive	Anti-lock braking systems, power features, air bags, electronic fuel injection	17%
Industrial	Robotics, high frequency welders, electronic pumps, uninteruptible power supplies, hvac, electronic lighting, automated production and processing, forklifts	36%
Consumer Electronics	TVs, cell phones, pagers, portable audio systems, hand tools, stereo amplifiers, battery chargers	9%
Government and Space	Communications satellites, surveillance satellites, nuclear submarines	8%

Source: International Rectifier. Annual Report for year ended June 30, 1997. <http://www.irf.com/whats-new/investor.html>. As obtained on February 24, 1998.

applications such as air conditioners and refrigerators because their switching speeds generate pulses that have a frequency range that is above human hearing (Baliga, 1997).

In 1996, the Commerce Department (1997) reported 35 companies manufacturing compressors or compressor units in the U.S.[2] Table 3-3 provides a list of selected HVAC manufacturers that potentially produce air conditioning compressors.

3.3.2 Industrial Motors

Industrial motors are being outfitted with smart power devices to provide speed control for a variety of factory machinery, equipment, and robotic systems. ASDs in industrial motors reduce electricity consumption by varying output power. Motors with ASDs are significantly more energy-efficient than constant speed motors for applications that operate a large portion of the time at partial loads. IGBTs also provide the ability to regulate input current more precisely than their predecessors.

Table 3-3. Selected Potential Manufacturers of Air Conditioning Compressors

Company Name

[2] Company names were not identified.

A-J Manufacturing	Hy-Save, Inc
Aeroequip	Landis & Staefa
Bailey Refrigeration	McQuay International
Carrier Corporation	MJC, Incorporated
Carson-Brooks Plastics, Incorporated	Nautica Dehumidifiers
The Clean Air Corporation	Peoples Welding Supply, Incorporated
Compressors Limited	SDI
Dunham-Bush	Team Management Systems
Dwyer Instruments	Trane Company
FHP Manufacturing	USA Manufacturing Corporation
Greystone Energy Systems	Venmar Ventilation
Honeywell Home and Building Control	Worthington Cyliner Corporation
Hudson Technologies	York International

Source: HVAC Online. Manufacturers list. <http://www.hvaconline.com//manufacturers/index.htm>.

Table 3-4 presents the major manufacturers of industrial motors and generators around the world. The industrial motors industry is capital intensive. Most firms are large multinational conglomerates with various business interests; smaller firms tend not to have the capital resources to compete against the larger firms. Companies compete for clients all over the world. Both Japan and the U.S. have six companies producing industrial motors, Europe has five, and India has one company. In general these companies are vertically integrated. Most companies, such as Mitsubishi Electric and General Electric, produce the semiconductors that are included in their drives, but others, such as Bharat Heavy Electricals, outsource.

3.3.3 High-Voltage Power Suppliers

High-voltage supply applications include electrical power distribution and transmission and locomotive drives. Table 3-5 presents a sample of companies that produce high-voltage power supply products. These companies produce highly specialized

Table 3-4. Worldwide Manufacturers for Industrial Motors and Generators

Company	Country
ABB	Switzerland
AEG	Germany

Bharat Heavy Electricals	India
BTR	UK
Emerson Electric	USA
Fuji Electric	Japan
General Electric	USA
GEC Alsthom	France
Hitachi Electric	Japan
Magnetek	USA
Meidensha Corp.	Japan
Mitsubishi Electric	Japan
Rockwell International	USA
Siemens	Germany
Teco Electric & Machinery	USA
Toshiba	Japan
Westinghouse Electric	USA
Yaskawa Electric Corp.	Japan

Sources: Profound. 1996. Selected excerpts from report entitled “World Manufacturers for Industrial Motors and Generators.” <http://www.profound.com>.

Information Access Corporation. 1998. Business Index [computer file]. Foster City, CA: Information Access Corporation.

Table 3-5. Sampling of High-Voltage Power Supply Manufacturers

Company	
Advance Hivolt	DEL Electronics
American High Voltage	EMCO High Voltage Co.
BC Power Systems	K and M Electronics, Inc.
Bertan High Voltage Power Supplies	Kaiser Systems, Inc.
Brandenburg	Magnetic Design Labs, Inc.
Continuum Power	Matsusada precision, Inc.
Cooper Power Systems	MCL, Inc.
Custom Made Transformers	Power Designs Inc.

Source: www.yahoo.com. 1998. Results of Yahoo! search of power supply manufacturers.

equipment for military and original equipment manufacturers’ applications. Manufacturers can custom design products to suit end-users’ needs (American High Voltage [AHV], 1998). Most manufacturers are medium-sized firms.

3.3.4 Automobile Electronics

In the automotive industry, IGBT devices are used in many systems, including voltage regulators, ignition, fuel injection, and power steering units. In the electric vehicles market, IGBT-based systems turn energy from fuel cells and batteries into alternating current for the engine. Table 3-6 lists a sample of 17 manufacturers of electronic devices for automotive applications. In some instances manufacturers are a subsidiary of larger conglomerates, but more commonly, manufacturers produce diversified electronic devices that are tailored to client specifications (Cherry Semiconductor, 1998).

Table 3-6. Selected Potential Manufacturers of Automobile Electronics

Company Name	
Allegro Microsystems	Harris Semiconductor
Analog Devices Incorporated	Hewlett Packard
Borg-Warner Automotive, Incorporated	Hitachi America, Limited
Burr-Brown Corporation	International Rectifier
Catalyst Semiconductor, Incorporated	KEMET Electronics
Cherry Semiconductor Corporation	Ledtronics Incorporated
Elantec Incorporated	Robert Bosch Corporation, Automotive Group
Exel Micro Electronics, Rohm Corporation	Rohm Corporation, Rohm Electronics
FI Automotive Information Services	

Source: Auto Industry Annual Service Guide. Obtained on February 27, 1998. <http://ai.chilton.net/cgi-win/cgiDir.exe/436147.000/AI?/prod=2;~5650~5700~/>.

3.3.5 Mobile Power Systems

Mobile power systems provide power for systems located in areas where electric power does not exist or when temporary power outages occur. These systems are used as power sources for telecommunication sites; home and industrial standby generators; recreational vehicles; and U.S. military ships, aircraft, and tanks. Table 3-7 lists a sample of companies that manufacture mobile power systems.

Table 3-7. Sampling of Mobile Power Systems Manufacturers

Company	
Abacus Controls	International Power Machines
Acme Electric Corp	Liebert Corp.
Alpha Technologies, Inc.	Merlin Gerin Electronics
American Power Conversion	Phoenixtec
Behlman	Piller, Inc.
Best Power Technology Inc.	Power Paragon, Inc.
Clary Corporation	Power Systems & Controls, Inc.
Deltec Power Systems, Inc.	Toshiba International
Elgar Corp.	TSI Power
Exide Electronics Group	Tripp Lite Manufacturing
Hewlett-Packard Corp.	Valence LLC
Instrumentation and Control Systems, Inc.	Wilmore Electronics Co. Inc.

Source: Profound. 1996. Selected excerpts from report entitled "World Manufacturers for Industrial Motors and Generators." <http://www.profound.com>.

3.3.6 Power Conditioning and Power-Device Control

Power conditioners and power-device controls are used to safeguard electrical systems and property from dangerous and harmful variations in power supply and quality. Conditioners, transformers, and regulators repair damage done to power by internal and external loads and demand fluctuations. They regulate the inputted and outputted currents to maintain power stability; they help eliminate power surges and loops that can cause serious damage to property (Wiremold, 1998). Start-up and shut-down of large electrical motors and the use of ASDs are common sources of power quality problems.

There are three general products in this industry: isolation transformers, ferroresonant power conditioners, and automatic voltage regulators. Isolation transformers are the midpoint between the power source and sensitive equipment. They are engineered to minimize noise and ground interference problems. Ferroresonant conditioners handle both isolation and regulation as well as offer protection against surges and harmonics (for a discussion of harmonics, see Section 2). Finally, automatic voltage regulators reduce or eliminate the effects of overvoltage and brownouts. In addition, they also protect against surges and isolate and regulate power. A list of manufacturers is forthcoming.

4 Technical Impact of Mathematical Modeling

In this section, we identify the quantifiable and nonquantifiable technical factors associated with using mathematical modeling of IGBT devices. For the manufacturing sector, the principal cost reductions resulting from mathematical modeling of IGBTs are likely to be concentrated in the R&D and manufacturing areas. This distinction between cost reductions in R&D and in manufacturing areas is important. For cost reductions in R&D, the unit of analysis is the number of times a design process is conducted. The use of mathematical modeling can reduce the number of design interruptions needed to develop a new product. These cost reductions occur each time a design process is conducted and are similar to the fixed cost in that they occur regardless of the number of units produced. In contrast, the unit of analysis for cost reductions in manufacturing is the number of units produced. Mathematical modeling increases design precision, thus allowing design of lower tolerances and safety margins. This lowers the material costs associated with packaging the IGBT in the final product.

Mathematical modeling of IGBTs affects buyers through improvements in product characteristics. Similar to manufacturing costs, the unit of analysis to measure benefits associated with changes in product characteristics is the number of units purchased. In addition, buyers may benefit from the acceleration of new product availability.

The following section provides an overview of a typical design process for products using IGBTs and identifies the role of mathematical modeling in the design process.

4.1 OVERVIEW OF THE DESIGN PROCESS FOR PRODUCTS USING IGBTS

Figure 4-1 presents an overview of the design process for products using IGBTs. A typical design process for circuit architecture includes a simulation by the system designer to check the device's performance, then a physical test of the device at high power. Because IGBTs are used at high power, the device manufacturer will not have off-the-shelf models in his or her component library. High power levels lead to subtle effects like parasitic losses and stray inductance that vary depending on product characteristics. In this case, the system designer will develop his or her own models using software products (such as SABRE and PSPICE) employing mathematical models.

In many cases a system designer "fails" a device for his or her application. In these situations the system designer will then work very closely with the device manufacturer to re-design the device for the power requirement. If the simulation models are accurate, they can result in significant cost reductions in the design process by reducing the number of iterations associated with "failures."

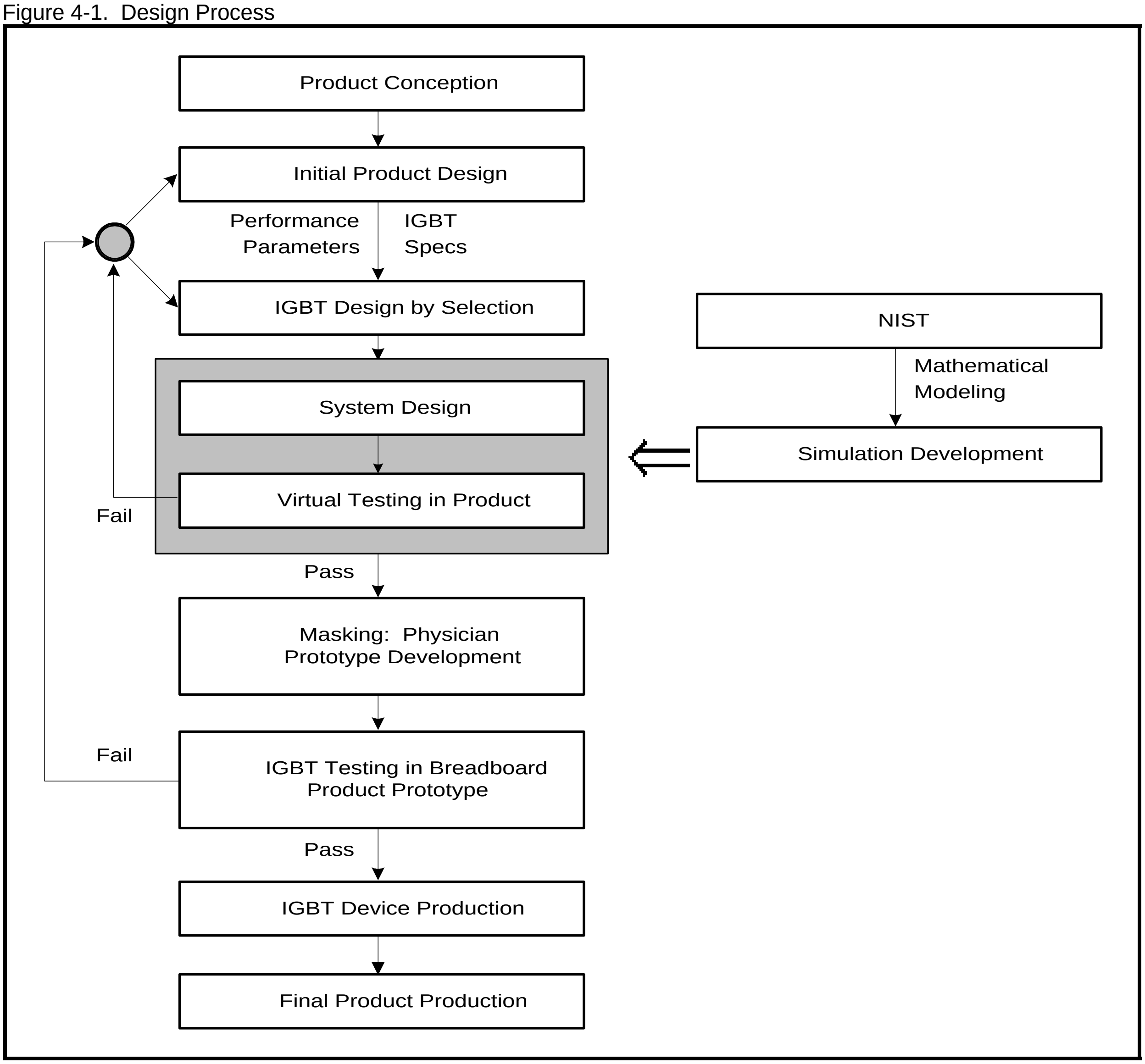
4.2 TECHNICAL IMPACT OF MATHEMATICAL MODELING

Simulation modeling based on mathematical models of IGBTs enables virtual testing of systems.[1] Virtual testing affects the design process in several ways:

- It enables representation of physical behavior of IGBTs' complex electrical characteristics in the silicon and how the device interfaces with the system design. Simulation modeling is particularly helpful in areas of thermal design and designs for transients and parasitics (Adler, 1997). Transients and parasites may arise from device and packaging parameters.

[1]Simulation modeling and virtual testing are often used interchangably.

Figure 4-1. Design Process



- IGBT designers gain an understanding of their design without physically procuring materials and building a prototype. Thus, they have shorter design cycles and avoided materials costs. Each time an IGBT designer modifies a design, an estimated $60,000 is spent for new mask sets, and there can be a delay of 8 to 12 weeks (Perry, 1997). Historically, IGBT design requires three to four iterations. With simulation modeling, a design may require only one to two iterations.

- System designers benefit from not having to wait 8 to 12 weeks between iterations. Historically, system designers physically test and fail an IGBT for their design. They would then work with the IGBT designer to tighten the IGBT specifications for their application. The simulation modeling based on mathematical models helps reduce the time delays and costs associated with design—enabling them to get a better and cheaper product to market faster.
- Mathematical models of IGBTs also affect the performance range of the system devices. Each IGBT has unique performance ranges. Mathematical modeling enables designers to test their systems at all ranges to determine if a given IGBT design will meet multiple design and performance requirements.

Simulation modeling also leads to increased performance of products employing IGBTs:

- More accurate information of the performance range of the IGBT enables increased efficiency of the product.
- Simulation modeling also will influence packaging design. Accurate simulation modeling may reduce engineering safety margins for packaging, which in turn reduces the cost of manufacturing.

5 Technical Barriers to the Adoption of Mathematical Modeling for IGBT Design

Uncertainty regarding the accuracy of mathematical models for designing IGBTs is the major factor limiting their use. Industry contacts indicated that SABRE is the most widely accepted model because it is more accurate than other models such as PSPICE. However, the general perception is that widespread use of modeling in the design process is limited because of concerns about model accuracy. Contacts from GE and International Rectifier indicated that current software applications were often not accurate enough for many of their applications.

Model accuracy is important because it affects the product design and the range of product performance. IGBTs have performance ranges that are a function of key design parameters. Model accuracy provides designers with the confidence that their systems will meet multiple design specifications and performance requirements, given the IGBT design parameters. Applications where models have the greatest accuracy problems are at high power levels. At high power levels subtle effects, such as parasitic losses and stray inductance, are difficult to model because they are highly dependent on key design parameters.

In addition, limitations in the accuracy of mathematical models are often driven by measurement uncertainty of design parameters.

Key design parameters differ with respect to the application. However, for most applications the key parameters, such as diffusion profiles and tolerance thickness, are difficult to accurately measure. Relatively small uncertainties in the measurement input parameters can lead to significant uncertainties in the modeling results. And in many instances these parameters are proprietary information that cannot be shared between device manufacturers and system design companies.

A generic concern of system designers is that theoretical models do not have the capability to predict distributional behavior of system devices. Steve Clemente of International Rectifier expressed concern that current simulation models cannot be used to design systems because a statistically based model is needed. The need is for a model that is based on a population of devices and that can incorporate how variations in parameters affect the behavioral distribution of the system. Current software containing mathematical models, such as SABRE and PSPICE, are not statistically based. Repeated modeling can be conducted to develop behavioral distributions as a function of parameter ranges, but this would be very costly and time intensive.

Dr. Baliga emphasized the importance of incorporating package-related parasitic circuit elements on the performance of IGBTs when designing high switching speed applications such as uninterruptible power supplies. For high switching speed applications, the series resistance and inductance of leads bonded to the chip and the screened metal runs become quite significant. Any model for the IGBT must incorporate these circuit elements. It is not practical to characterize the IGBT as a semiconductor chip. Each device must be individually characterized when mounted in the specific package as a composite unit. And the package characteristics depend on the power level of the application. Small devices used for lower power levels are individually encapsulated in plastic packages. At higher power levels, the chips are assembled into a “module” that contains many components—typically several IGBTs, rectifiers, and the gate drive circuit.

Although our analysis is focusing on the mathematical modeling of IGBTs, when assessing issues of accurately modeling IGBT performance in applications, the modeling of power rectifiers becomes equally important and has to date been problematic. Even if a perfect methodology for modeling the IGBT became available, the industry would not be able to use this capability if the modeling of rectifiers was not concurrently developed and made available in the same software.

Current simulation software has difficulties modeling IGBT devices in a predictive manner. Specifically, industry is looking for models that extend the "what if" capabilities and can be used to extrapolate outcomes (Bola Aromolaran, Motorola). Extrapolation capabilities would reduce modeling costs and be useful when modeling devices with high levels of uncertainty for key parameters.

Cost was also indicated as a barrier to the use of mathematical models. For high voltage applications, design manufacturers often do not have the appropriate models in their component libraries. In addition, early versions of models typically had long run times and convergence problems and were cumbersome to use. Significant improvements have been made over the past few years in these areas. However, our discussions with industry contacts indicate that these previous perceptions may still be affecting the adoption and use of mathematical models for IGBT design.

6 NIST's Contributions

NIST has contributed to modeling IGBT power devices through advances in

- circuit-simulator modeling,
- device design,
- model parameter extraction,
- circuit utilization, and
- model validation.

Circuit-simulation design, model parameter extraction, and model verification are all infratechnologies that stimulate R&D, improve the efficiency of R&D, advance industry's technological opportunities, and promote technology adoption. The term "mathematical modeling" is used to refer to this group of infratechnologies.

6.1 NIST'S TECHNICAL CONTRIBUTIONS

NIST's primary technical contribution to simulation modeling of IGBTs is the development of the mathematical model that predicts device performance. NIST's model enables the representation of the physical behavior of IGBT's complex electrical characteristics in the silicon. The mathematical models developed by NIST are the basis for virtually all the simulation software products currently used for IGBT system design in the U.S.[1] The NIST model is the

[1]Steve Clemente from International Rectifier indicated that the University of Zurich was developing similar modeling capabilities, but no industry contacts we spoke with indicated that they were using foreign models.

most accurate and complete mathematical model for IGBTs and is regarded as the universal standard (Getrue, 1997).

In addition, NIST has developed procedures for determining the key parameters of IGBTs that must be incorporated into the modeling process to accurately simulate the performance of the device. Such parameters may include, for example, the area of the device and the lifetime of the carriers of electronic charge in the semiconductor materials.

NIST has worked closely with software companies, such as Analogy and MicroSim, to facilitate the incorporation of NIST's mathematical models into commercially available software products. NIST's models are in the public domain, and from Dr. Hefner's papers designers can conduct the simulation without using software products, such as SABRE or PSPICE (Shen, 1997). However, using these software products greatly simplifies the modeling process. Analogy and MicroSim have developed the required interface to enhance user friendliness and have incorporated advanced solution algorithms, such as enhanced Newton step methods or sample point numerical arrays.

6.2 NIST'S IMPACT ON THE USE OF SIMULATION MODELING

Several contacts from device manufacturers and system design companies stated that NIST has had a "significant" impact on the development and use of simulation modeling using mathematical models. The general consensus is that software for circuit simulation modeling would have been developed in the absence of NIST's efforts. But the models would not have been as accurate and hence would not have penetrated the market as quickly as the products using NIST's mathematical models (Shen, 1997; Getreu, 1997).

NIST's contributions to the development of mathematical modeling have affected the use of simulation modeling of IGBTs in the following ways:

- increased the accuracy of mathematical models used in software products such as SABRE and PSPICE,

- Z accelerated the adoption of circuit simulation models and virtual prototyping by system designers and device manufacturers, and
- Z lowered the cost of software development for software companies such as Analogy and MicroSim.

Whereas mathematical modeling has had a significant impact on the IGBT design process and the range and performance of the systems, industry contacts did *not* indicate that mathematical modeling had had a significant impact on the number of products employing IGBTs or on the sales of products employing IGBTs. Industry experts indicated that the availability of mathematical modeling has not influenced their companies' overall product development decisions. In other words, even though modeling significantly reduced design time and design cost, this impact has not contributed to decisions to develop and market new products. In addition, the typical schedule for new product development is driven primarily by manufacturing and tooling constraints and not by design constraints (Baliga, 1998).

Thus, our analysis of NIST's contributions to mathematical modeling focuses primarily on the cost reductions associated with the IGBT system design process and on incremental efficiency improvements in end products employing IGBTs. We assume that using mathematical modeling for IGBT system design has not significantly influenced the number of products employing IGBTs or the timing of manufacturers' decisions to incorporate IGBTs into their products. In addition, we assume that the benefits resulting from using mathematical modeling have not significantly affected consumer demand for products employing IGBTs. Our detailed approach for modeling the economic impact of NIST's contributions will be presented in the Task 3 report.

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Appendix A: Telephone Interviews

The following summaries are in the order that they occurred. Because of time constraints it was not practical to ask the contacts all of the questions previously scripted. In each case the call was intended to result in the most information with the least difficulty for the contact. At the end of each interview the contact was asked about availability for future consultation. Each contact's answer is indicated as the last item of his/her summary.

November 7, 1997

Dr. B. K. Bose — **Applications**
Condra Chair of Excellence in Power Electronics
University of Tennessee
(423) 974-8398

Dr. Bose is aware of pioneering work done by Hefner at NIST. He identified the "Hefner model" as an original contribution being used by others—"seen references in papers." He, however, does not use the model and cannot comment on industry's use of the model. Dr. Bose would not be appropriate to contact for further information.

November 7, 1997

Don Burke — **Devices**
Director of Engineering
Harris Power Semiconductor
(717) 474-3254

Mr. Burke is aware of Hefner's work and states that it has had SIGNIFICANT impact!!!!! Harris uses SABER software from Analogy based on Hefner's equations. They use SABRE both internally for IGBT design and also provide SABRE models to customers for use in circuit modeling. These models enable circuit designers to accurately represent the device being manufactured that incorporates Harris's IGBT. Specifically the models enable customers to predict how Harris's product will work in their device. Mr. Burke identified SABRE as the most accurate model available. It is possible that in the future circuit simulators will be the only way Harris communicates technically with their customers.

Harris uses MicroSim for other power MOS devices—did not have accuracy of SABRE for IGBT. They chose MicroSim for the MOS application because it was less expensive and more of their customers use MicroSim's PSPICE for the MOS applications.

Mr. Burke credits NIST with accelerating the development of SABRE for IGBTs. However, similar work is being done in other countries, so eventually it would have evolved here too. Burke appreciates the help NIST has provided the industry with these tools; however, via SABRE, the tools are also helping foreign competitors, although the model was developed with U.S. tax money. Harris has benefited from Dr. Hefner beyond his impact on SABRE. Dr. Hefner has helped Harris with seminars and consulting.

Mr. Burke identified numerous benefits from SABRE, including that it

- saves the circuit designer from being wrong and that saves money,
- enables the designer to do “what if” in a less expensive and quicker way,
- is a higher level language (more powerful and user-friendly) than SPICE (SPICE was developed at Berkeley a while ago, MicroSim has products based on SPICE—PSPICE which is not as accurate as Analogy for IGBT),
- enables representation of physical behavior of the IGBT’s complex electrical characteristics in the silicon, and
- helps designers avoid surprises by increased accuracy.

Mr. Burke identified the benefit chain as follows:

- analogy benefits from Hefner’s model with better product and thus greater sales,
- IGBT designers benefit by having a better design process and better communication with circuit designers,
- circuit designers benefit by enabling less expensive “what if” and by avoiding errors in prototypes, and
- end users benefit by getting a better product possibly cheaper.

The term interoperability is not common to the industry. Mr. Burke is available for further consultation.

November 7, 1997

Michael S. Adler — **Applications**
Manager Control Systems and Elec. Tech. lab
General Electric
(518) 387-5882

Mr. Adler was not aware of NIST or Dr. Hefner specifically. He is familiar with IGBT power devices and modeling. Mr. Adler's group at GE uses SABRE to simulate power circuits for power supplies of inverters—AC to DC, VFD, etc. Although the SABRE model is not totally accurate for the application, sometimes GE even uses it to model motors. His group uses the models for high power applications of IGBT—to 1 MW. There are no high power device manufacturers in the U.S., most of the U.S. manufacturers are medium power producers. The device manufacturers he identified are:

Medium Power	**High Power**
Harris Semiconductor	ABB
International Rectifier	Mitsubishi (PowerX markets products in U.S.)
Motorola	Hitachi
Siliconix	Toshiba

A typical design process for circuit architecture would include a simulation to check performance of the device in the GE design and to check stresses, then a test of the device at high power. In general because GE is using the devices at high power the device manufacturer does not have the models in their library; thus GE develops many of their own models for SABRE. The high power levels have subtle affects like parasitic losses and stray inductance that affect product design. In many cases GE "fails" a device for their application. In these situations they work very closely with the device manufacturer to re-design the device for the power requirement. If a model is accurate it can result in BIG savings. Areas that may be helpful include thermal design and designs for transients and parasitics. Transients/parasitics may arise from device and packaging parameters.

The benefits that these models provide at each industry level include

- Z faster design,
- Z better product, and
- Z lower cost.

Mr. Adler recommends contacting: John Hooker
GE Industrial Control Systems
Fort Wayne, IN
medium power motor technologies

Potential targets for a broader survey should include IEEE societies like Power Electronics and Industry Applications.

November 7, 1997

Ian Getreu — **Software**
Vice President
Analogy Inc.
(503) 520-2716

Obviously Analogy is aware of NIST and Dr. Hefner's work. Dr. Hefner developed his IGBT model using Analogy's software and the model is now available in SABRE. The model was later converted to work in other company's products but was not as good in the other's products because of conversion problems. Mr. Getreu was not sure whether MicroSim's PSPICE uses the model. Another modeling software company that probably does not have it is Intusoft.

There are two applications of SABRE for IGBT—using Hefner's model:

1. to create IGBT devices
2. to use IGBT devices in a larger system

The majority of users of the software are in the second group. Industries include transportation, aerospace, and anything that requires switching medium power circuits.

When asked about how the software benefits its users, Mr. Getreu indicated that Hefner's model enabled the ability to create accurate application models. Specifically:

- Z Enables virtual prototyping?—Yes
- Z Decreases cost of custom design?—Possibly, it is a tool
- Z Decreases design time of custom devices?—Yes
- Z Decreases system's design time?—Yes

Z Enables development of devices with increased capabilities?—Yes, makes sure it works

The NIST model is the most accurate and complete mathematical model for IGBTs. It is regarded as THE universal standard. Without NIST's contributions Analogy would have developed an IGBT model but it would not have been nearly as good. NIST's efforts have had significant impact on this area. Yes, NIST's efforts also accelerated the introduction of this type of model.

Mr. Getreu identified the Analogy SABRE Simulator User Resource group—ASSURE—as a potential target for end users of the model. The appropriate contact at Analogy for this group is:

Craig Siegel
503-520-2725

Mr. Getreu is available for further consultation.

November 10, 1997

Frank Wheatley — **Devices**
Consultant to Harris
(717) 788-2319

Mr. Wheatly is aware of Dr. Hefner's work and has worked with him in the past. He seemed somewhat sensitive about the subject and giving NIST credit. When asked to comment on the industry structure he could not offer suggestions relating to software companies and felt that we had an accurate list of the major U.S. device manufacturers. The applications for the technology he identified were electric/hybrid automobiles, motor controls, and power supplies. He stated that Hefner's model may or may not be useful to the IGBT manufacturers like Harris; the major application for Hefner's model would be the system designer using the IGBT. Because of limited time he recommended that we contact:

Stan Benjakowski
Harris (PA)
717-474-6761

Stan has worked with Mr. Wheatly and Dr. Hefner on their models and his own models. Mr. Wheatly did not seem open to additional conversations.

November 10, 1997

Dan Artusi — **Devices**

Motorola
(602) 244-4879

Mr. Artusi is no longer working in a business area related to IGBT. He has been working in a totally unrelated area for about 2 years. His replacement would be a good contact:

Bola Aromolaran
Dir. Prod. Dev. Semicond.
602-244-5743

November 10, 1997

Glenn Perry — **Software**
Leader of Modeling Group
Analogy Inc.
(503) 520-2709

Mr. Perry had limited time so I focused the call on the areas about which Ian Getreu had specifically recommended speaking with him. Mr. Perry identified the following software companies that may or may not be using NIST's model:

- Analogy — Yes
- MicroSim — Yes
- Mentor Graphics — ?
- Intusoft — ?
- Cadence — ?

He felt our list of major U.S. device manufacturers was accurate. The major applications of IGBT include automotive, aerospace, power supply, and power transmission (small).

Mr. Perry warned of several challenges in surveying this industry. First, it will be difficult to get accurate data because many of the users of the simulators that incorporate the NIST model will be unaware that they are using the NIST model. Within a company there is usually one model expert and hundreds of users. The model expert understands the subtleties that the users are unaware of. Also, Mr. Perry has had difficulties getting responses to surveys that he has done in the past.

The NIST model benefits the industry in numerous ways:

1. IGBT designers gain an understanding of their design without physically procuring materials and building a prototype. This equates to shorter design cycles and avoided materials costs. Each time an IGBT designer

modifies a design there is a MINIMUM of $60,000 spent for new mask sets and a MINIMUM delay of 8 weeks. Historically, an IGBT design required three to four iterations. Now, a design may require only one iteration.

2. System designers benefit from not having to wait 8 to 12 weeks between iterations. Historically, a system designer would physically test and "fail" an IGBT for their design. They would then work with the IGBT designer to tighten the IGBT specs. for their application. The NIST model helps reduce the time delays and costs associated with design—enabling them to get a better and cheaper product to market faster.

3. The end user gains a better, more reliable product with lower warranty costs.

Hefner's model offer advantages by including

- all nonlinear capacitances,
- nonlinear leak characteristics,
- soft-knee breakdown,
- weak inversion characteristics, and
- body diode forward and reverse recovery mechanisms.

Mr. Perry recommends working with Dr. Hefner to identify appropriate contacts to survey. Analogy may be able to provide a list of customers. He will need to look into this because of issues relating to the value of their customer list and the danger in releasing it externally.

November 10, 1997

Eve Shen — **Software** Engineering Manager
MicroSim Corp
(714) 788-6080 ext. 7161

Ms. Shen is aware of Dr. Hefner's work. MicroSim has incorporated a version of Dr. Hefner's model into their PSPICE simulator that was developed under SRC funding at the University of Florida. Their first product with the model reached the market about 2 years ago as PSPICE version 6.3. Newer versions of PSPICE—7.0, 7.1, and 8.0—have all incorporated the model.

Typical customers of their software with the NIST model are companies that have large systems that require power distribution and control; large arrays of high-current, high-voltage devices; or uninterruptible, stable power supplies. One example is a traffic system. An example company is ABB.

Ms. Shen's answers to how the NIST model benefits users are as follows:

- Enables virtual prototyping?—IN GENERAL NO, BUT FOR IGBT YES. BEFORE THE NIST MODEL VIRTUAL PROTOTYPING OF IGBT'S COULD NOT BE DONE.
- Decreases cost of custom design?—YES
- Decreases design time of custom devices?—YES
- Decreases system's design time?—YES
- Enables development of devices with increased capabilities?—YES

Also, the model increases the yield of systems. For example, each IGBT has performance ranges. The model enables a designer to test their systems at all of the ranges and know if a given IGBT design will meet multiple designs and performance requirements.

What advantage does NIST's model offer?

Ms. Shen was not aware of any other intrinsic model in the public domain. From Hefner's papers a designer can do the simulation without PSPICE, but PSPICE greatly simplifies the process. Without the intrinsic model the user must compose a subcircuit that resembles the IGBT. This process can be as accurate, but it is far more difficult. The NIST model enables faster run time but no significant accuracy advantage.

Without NIST's contributions would your company have pursued these modeling capabilities?

Ms. Shen was not sure exactly how NIST impacted the model because of the relationship with SRC and University of Florida. She didn't know exactly who had done what or who owns what intellectual property. The contact at the University of Florida is Dr. Ngo.

MicroSim is currently merging with OrCAD. In mid-December the merger should be complete and Ms. Shen's job will be eliminated. For this reason if we are to speak with her again, it needs to be before December 15, 1997. There is information on MicroSim and PSPICE on the World Wide Web at http://microsim.com.

November 11, 1997

Steve Clemente — **Devices**
Director of Applications
International Rectifier
(310) 322 3331

Mr. Clemente is aware of Hefner's and NIST's efforts. His comments on the industry structure identified MicroCap and HPSICE as additional software players—he was not sure whether these are company or product names. There are also software companies that have products that generate models for the simulators. The major device company list is accurate for the U.S. and the foreign players are Thompson and Siemens in Europe and then the Japanese companies. The major applications are motor drives, power supplies, microwave ovens, and TV deflection.

There is no typical design process; the variations are huge. Simulation is the least used tool in system design because it takes time and is expensive—especially SABRE. Most efforts do not warrant simulation. He believes that simulation cannot be used to design systems because a statistically based model is needed—SABRE is not statistically based. The true need is for a model based on a population of devices. He believes this is why SABRE has not really yet left the academic setting. SPICE has the same problem. These programs can be used for a first cut in early prototyping. They are very useful to the IGBT designer, although there are other tools available for this too—PISCES and a package from the University of Zurich.

At the IGBT level there is a savings relating to mask sets and the models enable the product to reach the market sooner. These types of software tools have not yet affected how IR communicates with their customers, but Mr. Clemente believes it eventually will. IR has not yet reached that point. Mr. Clemente believes that NIST's efforts accelerated the development of these types of software tools.

International Rectifier's products range from devices to finished goods. They use SABRE, SPICE, and software from the University of Zurich for IGBT-related efforts. Mr. Clemente is open to further conversations.

November 11, 1997

Bola Aromolaran — **Devices**
Motorola
Dir. Prod. Dev. Semi-cond.
(602) 244-5743

Mr. Aromolaran was not directly familiar with NIST's modeling efforts. Mr. Aromolaran's group makes IGBTs for power devices. Their products are used in power supplies, personal computers, and power regulators. They use MSPICE, a Motorola simulator based on SPICE. Their Automotive Group uses SABRE and may be good to talk with. The contact is:

Mr. Kim Gauen
Applications Engineer
Motorola Automotive Group
765-455-5119

Mr. Gauen's group uses SABRE for modeling Motorola's devices for their customers' use in ignition switches.

Currently Mr. Aromolaran's group is having trouble modeling IGBT devices in a predictive manner. He has not found many models that are predictive for IGBTs. One of his modelers is familiar with Hefner's work and has discussed predictive models with him. Specifically, they are looking to have a model that extends the "what if" capabilities to extrapolate outcomes. He does not think Hefner's work does this.

I specifically clarified some of the terminology with Mr. Aromolaran. We are correct that the industry calls IGBTs devices. The circuit designer is at the application level, also known as the system level. In general, he confirmed our terminology. Mr. Aromolaran recommends that we contact Gary Dashney of his group for further conversations. Mr. Dashney was not available at the time of my inquiry, so Mr. Aromolaran provided what he knows. Mr. Dashney is far more aware of issues relating to IGBT modeling. Mr. Dashney can be reached at 602-244-3471.

November 12, 1997

Stan Benjakowski — **Devices**
Harris Semiconductor
(717) 474-6761

Mr. Benjakowski was aware of Alan Hefner's model being implicit in SABRE as a primitive. About 7 years ago Harris became aware of the model from Analogy. Other than Analogy and MicroSim, the only software company that offers an IGBT model that Mr. Benjakowski is aware of is a new company called Magsoft. He believes that the model is their own.

The applications for IGBTs fall into two categories: power supplies and motor control. The typical design process described by Mr. Benjakowski is as follows:

- device manufacturer works closely with the circuit designer—their customer
- customer typically provides a specification
- Harris determines if they can build the device, if so…
- Harris develops a process to manufacture the die and build the device using a simulator and FEM tools
- Harris builds a prototype and sends to customer
- customer plugs prototype into breadboard
- customer either accepts device and Harris goes into production, or
- customer asks for changes which Harris works closely with customer in future iterations

Typically, the design process for IGBTs has been a disadvantage versus the design process for MOSFETs. MOSFETs use simulation to do the prototyping in the system versus the IGBTs, which are typically tested in a breadboard configuration. Slowly, as a result of the Hefner model, IGBT system designers are starting to use simulation and ask for models from Harris.

Harris uses both SABRE and PSPICE. They generally use PSPICE for power MOSFETs because it is less expensive and provides a workable solution. For IGBTs they generally use SABRE because of the accuracy advantage.

One of the reasons that simulators for IGBT are becoming more common is because the system designers are relying more heavily on the device manufacturer in the design process. The larger companies have been downsizing in recent years, which has required them to lay off experts. With less expertise in-house the companies request engineering support and help with circuit simulation—especially when problems are encountered. The interaction between the device manufacturer and system designer has changed drastically in the last 5 years. Historically the device manufacturer would provide a spec sheet to the circuit designer. Today it is more common for the device manufacturer to provide a model of the device and have greater interaction in the preliminary design process.

Hefner's model is the best IGBT model available. The other models are typically macromodels that take much longer to run and have convergence problems. NIST has helped IGBTs compete with MOSFETs and SABRE based on Hefner's model is the most widely accepted model. PSPICE has less accuracy than SABRE.

Mr. Benjakowski indicated that it may be possible to get a list of Harris customers as potential target survey participants. The appropriate person to contact at Harris about this is:

Fred Lokuta
717-474-3273

Mr. Benjakowski would be happy to continue to discuss the IGBT industry or identify engineers at Harris that use the model.

Future Contacts—In addition to those contacts previously indicated as available for further consultation.

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