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Using Power Diode Models for Circuit Simulations—A Comprehensive Review

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***Abstract*—In recent years, a number of new models for the power diode have been proposed. The objectives of this paper are to provide the power electronics community with a comprehensive review and summary of recent power diode models. The models have been categorized systematically according to their modeling concepts with objective comparison of their status pertaining to the various modeling issues. A summary table has been created to aid power circuit design engineers and power rectifier device engineers in selecting appropriate models for their applications.**

***Index Terms*—Circuit simulation, power semiconductor diodes, semiconductor device modeling.**

I. Introduction

IF THE standard SPICE diode model is used to simulate a high-voltage high-current diode, the forward and reverse recovery characteristics are not satisfactorily predicted. Fig. 1 shows a typical experimental trace of the current through a high-power diode when it is being turned off. The SPICE simulated response is also shown. The soft recovery of the power diode cannot be simulated by the SPICE diode model, leading to erroneous predictions of switching power dissipation.

Another drawback of the SPICE diode model is its inability to simulate the forward recovery, as illustrated in Fig. 2. When a diode turns on abruptly under the influence of the external circuit, a sharp voltage overshoot occurs across the diode. This due to a number of factors, the chief of which is the finite time taken by the conductivity modulation process in the bulk of the diode. The fixed internal resistance used in the standard model is inadequate for predicting such characteristics.

In recent years, a number of new models for the power diode have been proposed. Most of them were shown in their respective papers to be able to overcome the drawbacks of the standard SPICE model to a certain extent. However, for practicing engineers in the power electronics community, the most pressing issue is which of these models to adopt for their computer-aided design and analysis. The number of modeling concepts and techniques used in the reported models can be bewildering to these engineers, who just want reliable models to simulate their power electronic circuits. In addition, other side issues, such as accuracy of simulated results, validity range of the models, compatibility with existing simulators, implementation know-how, convergence performance, availability of model parameters and parameter extraction techniques, arise when considering which of the models to adopt.

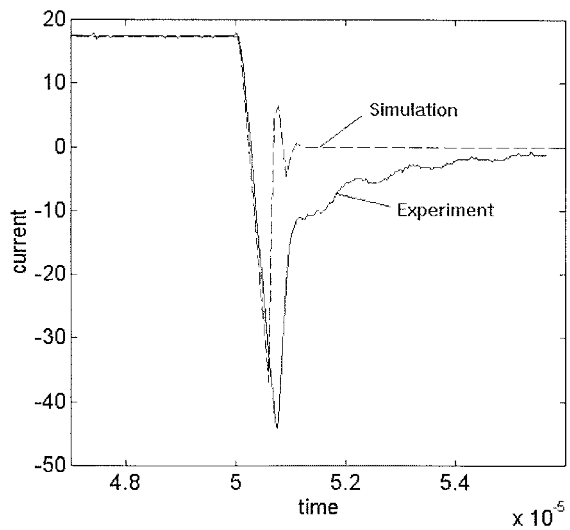

Fig. 1. Inability of standard diode model to simulate soft reverse recovery in power diode current.

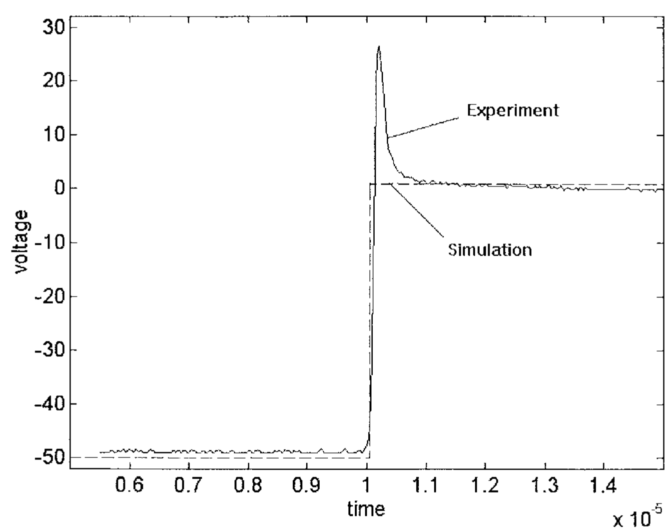

Fig. 2. Inability of SPICE diode model to simulate forward recovery in power diode voltage.

The objectives of this paper are to provide the power electronics community with a comprehensive review and summary of recent power diode models. The models are categorized systematically according to their modeling concepts with objective comparison of their status pertaining to the various

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modeling issues. It is the hope of the authors that the review, categorization, and discussion will help to provide engineers with selection guidelines for models for their end applications.

II. Issues in Power Diode Modeling

The more important issues that should be addressed when selecting power diode models for power electronics CAD are discussed here. This discussion will help to elicit a more focused review of recent models.

A. Model Formulation Techniques

The most fundamental aspects that distinguish among different power diode models is the model formulation technique and concept employed. Classifying these concepts is not straightforward, as different literature attached somewhat different interpretations to the terminology involved. Very broadly, all models may be classified either as micromodels, or as macromodels. Micromodels are closely based on the internal device physics and, if properly formulated, should yield good accuracy over a wide range of operating conditions. Because device physics unavoidably require mathematical equations, micromodels are also known as mathematical models. Macromodels reproduce the external behavior of the device largely by using empirical techniques without considering its geometrical nature and its internal physical processes. This external behavior is usually modeled by means of simple data-fitting empirical equations, lookup tables, or an electrical subcircuit of common components to emulate known experimental data. Because of the latter reason, macromodels have been mistakenly labeled as subcircuit models. Many so-called subcircuit models are actually micromodels because they used subcircuits to simulate fairly complex physics-based mathematical equations. In our review here, the term subcircuit refers to the mode of model implementation rather than the model formulation technique.

Macromodels were frequently reported in the earlier literature, before the 1990's. However, because of their limitations in terms of accuracy and flexibility, they are rarely utilized nowadays. Micromodels are generally more computationally efficient, more accurate, and more related to the device structure and fabrication process. Most models proposed in the 1990's are micromodels, which can be further classified as numerical models, analytical models, and hybrid models.

Numerical modeling uses the partial differential equation set of the semiconductor physics and solves them using finite-element or finite-difference methods. These equations describe the physical phenomena within the semiconductor, consisting of carrier drift and diffusion components, carrier generation and recombination effects, and the relationship between space charge and electric field. These models are sometimes further classified either as exact or as simplified. The term "fully" or "exact" refers to the solutions of the complete system of basic equations without simplifications. From the engineering point of view, the degree of accuracy that is achieved by an exact numerical model is not always necessary or even justified, in particular, if the input data, such as the doping profile, is only known with a limited accuracy. In such cases, simplified numerical models may suffice. The simplifications may be in the form of assumptions made to semiconductor physics, or in the finite-element algorithms. Numerical models are suitable for device manufacturers who want to evaluate the performance of their devices in power electronic circuit applications.

Analytical micromodels rely on a set of mathematical functions to describe the devices' terminal characteristics without resorting to finite-element methods. Examples are the standard diode and transistor models packaged in SPICE. There has been a school of thought that analytical models can never fully predict the characteristics of power devices. However, this is not necessarily true, as the mathematical equations can always be formulated to predict the characteristics as accurately as possible, at the expense of computational overheads. These equations could also be device physics related to provide realistic simulations over a wide range of operating conditions. Like numerical modeling, the limits to simulation accuracy are more due to the accuracy of the input parameters rather than due to the models themselves.

The computational overheads of analytical models are far lower than those of numerical models. In addition, there is a large pool of popular commercial simulators, such as SPICE and Saber, the solver algorithms of which have been evolved to solve these types of models most efficiently. Having power device models in the libraries of these simulators allows the latter to function as general purpose power electronics circuits CAD tools. Analytical models are, thus, very appropriate for simulation of power electronic circuits over a large number of switching cycles.

A third type of micromodel formulation technique is to use a combination of numerical and analytical models. The motivation behind such hybrid model arises from the fact that certain physical phenomena in power devices are very difficult to simulate realistically using only analytical equations, particularly the charge storage effects in the lightly doped drift regions. The basic idea of this method is to use a fast numerical algorithm that solves the semiconductor equations in the drift region only. Analytical equations are applied to the rest of the device structure. This procedure has the advantage that a high accuracy of the charge carrier behavior may be simulated without the long execution time associated with fully numerical models. This type of models is suitable for very detailed study of device interactions with the rest of the circuit over a few switching cycles, e.g., snubber design.

B. Circuit Simulator and Model Implementation

Any model formulated would require a circuit simulator as a vehicle for simulation. In some early reported work on power device models, entire circuit simulators were created together with the models to demonstrate the application of power electronics simulation. This is no longer necessary nor practical nowadays, as there are numerous commercial circuit simulation software packages that come complete with professional graphics user interface and vast libraries of electronic component models. The research focus has, therefore, currently shifted to power device model formulation, instead of creating new power electronic simulator from scratch.

For numerical models, finite-element semiconductor simulators such as MEDICI are available. These simulators are usually equipped with rudimentary SPICE-type time-stepping solvers. The drawbacks are extremely slow simulation times, and not all power semiconductor devices physics are included, as these simulators were originally created for microelectronics applications.

Analytical micromodels can be implemented in commercial simulators by the insertion of mathematical equations. The method of insertion varies from one simulator to another. In PSpice, the technique is known as analog behavioral modeling (ABM) and is based on subcircuits of user-defined controlled E-type voltage sources and G-type current sources. These sources allow transfer functions for nonlinear devices to be specified by mathematical expressions, lookup tables, Laplace transforms, or frequency-response tables. Saber offers its own proprietary analog hardware description language called MAST to facilitate the incorporation of new device models in the form of templates. The templates can also call up foreign subroutines written in C or Fortran languages.

Hybrid micromodels involved many mathematical equations to solve the finite-difference portion of the model. Subcircuit form of implementation becomes very unwieldy and is, therefore, not practical for simulators such as PSpice. Simulators that provide powerful simulation languages such as Saber are required for this type of models.

C. Convergence Performance

Another important issue is how fast and convenient the simulation results can be obtained. It can be expected that numerical, hybrid, and analytical models generally have increasing simulation speed in this order. This is provided that convergence problems are not encountered. Many models proposed in the past have been discarded, because power electronics designers find that they frequently give rise to stalled and incomplete simulations. As a result, the standard SPICE diode model is still one of the most popular choices for modeling the power diode in power electronics simulations, despite its obvious shortcomings in terms of accuracy. In industry, there is little point in using a model that promises much but runs the risk of delivering little or even nothing when convergence difficulties surface. This is also the main reason why most commercial versions of SPICE do not incorporate any of the many micromodels reported in the literature so far.

D. Accuracy and Validity Range

Before a power diode model can be generally accepted and adopted by the power electronics community, its accuracy and validity should be thoroughly verified. Proposed models are usually reported in technical journals, where the limited paper length does not permit detailed presentation on the accuracy and validity range. Therefore, it may be necessary to write to the authors for more details before deciding on the adoption of the model. There is also the need to standardize test circuits for the power diode, e.g., the adoption of an "RG1" type of test circuit. Fig. 3 shows a typical current waveform obtained from such test circuit.

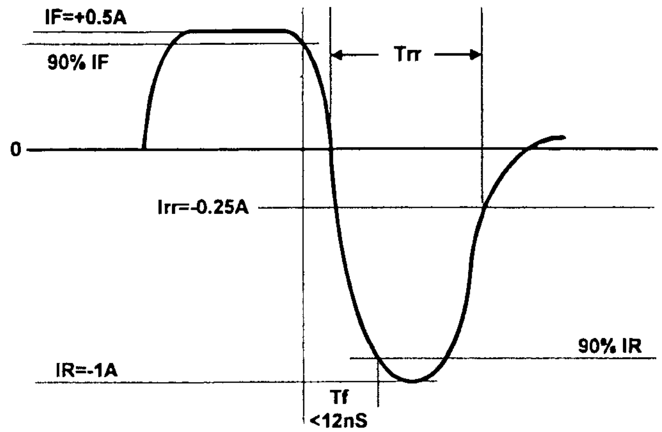

Fig. 3. Current waveform in RG1 reverse recovery test circuit.

E. Model Parameters Extraction

In numerical and hybrid models, it is necessary to have information on geometrical dimensions and the fabrication processes in order to obtain the necessary parameters for the models. Unless device manufacturers actively support the models by providing the parameters, it can be difficult for these models to be adopted by the circuit design community. Hence, the applications of numerical and hybrid models have so far been confined to the device manufacturers for the investigation of their own products.

For analytical models, it is usually possible for the user to figure out the parameters by comparing trial simulation results with sample experimental results. However, if a model requires a large number of parameters, the task of parameter extraction becomes tedious. Thus, the number of input parameters, as well as the availability of the parameter extraction procedure, should be important considerations.

III. Review of Recent Power Diode Models

Research in modeling of the power diode has been ongoing, ever since the p-n junction was invented, but it was in the last ten years that interest has picked up considerably, with the surge in power electronics applications. In this paper, only the models developed in this period are reviewed, as any significant contributions from earlier models would also have been included in the more recent models. Once again, the original SPICE diode model is used as a benchmark by which other models may be compared.

For easy referencing, the name of each model to be reviewed is given as the name of the first author of the particular published paper, followed by the corresponding reference number as listed at the end of the paper, and the year of the publication. For each review, the principle used in the model formulation, the assumptions (including any inherent assumptions in the derivation) made in the model development, the applicability of the model as a result of the assumptions, and the derivations of the model equations are discussed. A summary table of the various models discussed is provided at the end of the section to aid engineers in the power

TABLE I
LIST OF MODELS BASED ON LUMPED CHARGE CONCEPT

Model Name	Assumptions	Applicability/comments
Lauritzern [2] Model, 1991	a. Power diode is the p-i-n diode b. Equal hole and electron mobilities c. Base contraction due to the moving of the depletion region boundary is omitted, which resulted in single fixed time constant in the reverse recovery. In other word, the voltage dependent reverse recovery is omitted d. Forward conduction has attained a steady state e. di/dt is a constant f. Use of constant transit time which assume quasi-charge control model g. Emitter recombination due to high level injection is omitted.	a. Self-heating effect cannot be included b. Apply to power diode with low PIV so that base contraction may be neglected (i.e. short base diode) [6] c. The quasi-charge control model is valid only for I_{RM}/I_F <1.0 [7], where I_{RM} is the peak of the reverse current as shown in Figure 1.
Ma [3] model, 1993	The assumptions (a) to (g) are similar to that in Lauritzern [2] Model, plus h. turning on of the diode is from the zero bias state, instead of the reverse biased state	Comments are the same as in the Lauritzern [2] Model, with one additional comment: a. forward recovery results are valid only for the base region shorten than the diffusion length [7].
Ma [4] Model, 1993	Assumptions (a) to (f) are similar to assumptions (c) to (h) in Ma [3] Model.	The model applies to p-v-n power diode with low PIV, and negligible self-heating. The switching circuit is such that I_{RM}/I_F<1.0.
Ma [5] Model, 1997	a. During forward condition, the drift current is determined by the lowest carrier concentration in the region, and the higher concentration carrier can be ignored b. During reverse recovery, drift current is negligible c. Use of average carrier lifetime in the base region	a. The model accounts for DC and switching characteristics in low and high level injection conditions (with and without emitter recombination) b. The voltage dependent reverse recovery is included in the model c. No self-heating effect is included Therefore, the model applies to p-v-n diode at all conditions where self-heating is not significant, and the spatial variation of the carrier lifetime in the base region is not excessive.

electronics community in selecting an appropriate model for their applications.

A. Analytical Models

Several principles have been based in the development of analytical models. They can be classified as follows:

1) lumped charge concept by Linvill [1];
2) charge control model;
3) dynamic charge model;
4) asymptotic waveform evaluation method.

The lumped charge concept has been adopted by Lauritzen and Ma *et. al.* [2]–[5] from the University of Washington. The advantages of the models are easy to implement, easy parameter extraction and high computation efficiency. Table I lists the development of the models developed by them, and their applicability. One can see the progression of the model development from only the reverse recovery of p-i-n diode to forward and reverse recovery of p-v-n, including the voltage-dependent reverse recovery and emitter recombination effects.

The charge control model uses the charge control equation as in PSpice, so that the models can be implemented in PSpice. At the same time, the physical processes in the power diode can also be taken into account in the modeling. Table II lists the models developed based on the principle.

The dynamic charge model recognizes the dynamic nature of the charge distribution in the base region. This nature arises from the fact that the charge distribution in the base region depends not only on the instantaneous values of diode voltage and current, but also on the previous state of the diode. Table III lists the models in this category.

The asymptotic waveform evaluation method makes use of the continued fraction expression of the carrier distribution in the base region to convert the solution of the ambipolar

TABLE II
LIST OF MODELS BASED ON CHARGE CONTROL CONCEPT

Model Name	Assumptions	Applicability/comments
Liang [8] Model, 1990	This model developed a SPICE based circuit based on the semiconductor physical equations with the following assumptions: a. p+n and n+p diodes b. Very high transient slope for forward recovery c. Effective lifetime is a constant d. Base contraction due to the moving of the depletion region boundary is omitted, which resulted in single fixed time constant in the reverse recovery e. No emitter recombination is considered, making the model suitable for low and medium level injection	This model applies to p+n and n+p diodes with very high switching speed for forward recovery, and medium rating. The quasi-charge control equation used in the derivation make the model applies to the switching condition of I_{RM}/I_F <1.0.
Analogy [9] Model, 1995	Nothing can be said about the assumptions as the model equations and their derivations are not disclosed.	This model includes the temperature effect on the device performance.

diffusion equation into subcircuit. This principle is adopted by Strollo [13]. Only one assumption is known, and other assumptions made in the derivations cannot be known as its reference list is not provided. The one assumption is that $(\partial p(x_m, t))/(\partial x) = 0$ at a constant x_m where $w/2 < x_m < w$, and w is the base width. The model includes the effects of emitter recombination, depletion boundary movement, and conductivity modulation in the base region. Thus, the model seems to apply to the p-v-n diode at all conditions.

B. Numerical and Hybrid Models

There have been several numerical and hybrid models developed in the 1990's. One is for the p-v-n diodes developed by Vogler *et al.* [14], and another focused on the reverse recovery of abrupt p-n junction, which is developed by Winternheimer *et al.* [15], [16].

For the model developed by Vogler *et al.* [14], finite-difference method is employed to solve the ambipolar diffusion equation with only one assumption, that is, temperature >77 K. In the development of the model, the ambipolar diffusion equation includes the spatial dependence of carrier–carrier scattering, auger recombination, avalanche effects, doping and carrier lifetime profiles, and effect of buffer layers. Thus, the uses of the unphysical effective parameters, such as mean carrier concentration, average mobility, etc., are avoided. However, the self-heating effect is not included. This model has also been implemented in Saber as a hybrid model and used to simulate a hard-driven gate-turn-off (GTO) inverter [25].

For the model developed by Winternheimer *et al.* [15], [16], the physical processes in the semiconductor devices are carefully included, so that the model can predict the performance of diodes without any fitting parameters. The assumptions made in the derivation are as follows:

1) abrupt p + n and n + n junctions;
2) carrier lifetime is constant over time;
3) steady-state forward conduction;
4) emitter recombination is neglected;
5) excess charge in the swamped zone is approximated by straight line;
6) current in the space-charge zone is caused by holes only;
7) current in the resistance zone is caused by electrons only;
8) ratio dn/dx is assumed to be equal to dp/dx in the resistance zone;
9) diffusion current of holes in the space-charge zone is neglected.

As this model considered only the turn-off behavior, and self-heating is not included, it is applicable to the study of the reverse behavior of the abrupt p-n junction.

In view of the long computation time required by the numerical models, Goebel *et al.* [17], [18] developed a hybrid model. This model solves the differential equations describing the semiconductor device partly analytically and partly numerically with the following assumptions:

1) $\tau(T)$ is known, where T is temperature, and τ is carrier lifetime in the base region;
2) mobilities are affected by phonon scattering only;
3) conduction modulation only affects the resistivity of the lightly doped region. Its effect on the ambipolar diffusion length is neglected.

In this model, both static and dynamic self-heating are included. The derivation also allows nonsteady-state turn-on and turn-off conditions to be considered. The effects of mobile charge carriers in the space-charge region and velocity saturation of the carriers are included in the model. The trap density can also be included in the model, if desired. Therefore, this model can be applied to all p-v-n power diodes under various switching conditions, provided that $\tau(T)$ is determined experimentally. Table IV gives a list of models based on numerical and hybrid numerical concepts.

C. Empirical Model

There is only one empirical model developed since the 1990's, by Bertha *et al.* [19]. This model modifies an existing power diode PSpice model so as to reduce the number of ideal

TABLE III
LIST OF MODELS BASED ON DYNAMIC CHARGE CONCEPT

Model Name	Assumptions	Applicability/comments
Jin[10] Model, 1991	a. Modulated conductivity of the base region is given by the average concentration of excess holes and electrons b. Base width>$2L_a$, where L_a is the ambipolar diffusion length c. Emitter recombination is omitted	a. As base region resistivity is inversely proportional to the carrier concentration, the use of average concentration is not suitable b. Only forward recovery is considered This model applies to the study of forward recovery of p-v-n diode with base width larger than $2L_a$, and current is not too high that emitter recombination can be omitted
Kraus [7] Model, 1992	Charge carrier distribution can be approximated by polynomial expression	a. Effective transit time is used, and its value varies with diode voltage and the time rate of voltage change b. Effect of conductivity modulation on diffusion length is included, making the model valid for both short base region (less than the diffusion length) and long base region devices c. Mobile carriers in the space charge region and velocity saturation of the carriers are included in the Poisson equation for junction voltage calculation d. Temperature effect is included e. The degree of polynomial approximation of charge carrier distribution is fixed, which is somewhat arbitrary This model can be applied to any p-v-n power diode, and the effect of self-heating is also included. The accuracy of the model depends on the polynomial approximation accuracy.
Yang [6] Model, 1994	a. Ideal abrupt junction b. Constant I_{RM}, instead of di/dt during reverse recovery c. I_{RM}>>I_F	The model applies to p+n or n+p power diode. The reverse recovery circuit is RG1 type (Figure 3) of circuit with I_{RM}>>I_F.
Tseng [11] Model, 1994	a. Low & medium level injection b. Base contraction due to the moving of the depletion region boundary is omitted, which resulted in single fixed time constant in the reverse recovery. In other word, the voltage dependent reverse recovery is omitted.	The model applies to power diode with low and medium current rating such that high level injection will not occur, and PIV is not too large that the effect of moving boundary of the depletion region is insignificant
Tseng [12] Model, 1997	The model modifies the quasi-static charge equation by including the dependency of excess charge in the base region on the rate of the change of the excess charge. The conductivity modulation during forward transient is also linked to the excess charge. The assumptions made in the derivation are: a. Long n-base diode b. Constant minority carrier lifetime (i.e not spatial dependent) c. Linear dependence of conductivity with the excess charge	a. No emitter recombination and carrier scattering are considered, which limit the applicability to medium level injection b. Only transient behavior is described Hence, the model applies to long base p-i-n diode with varying switching conditions at low and medium level injection

components in the model. In the derivation of the model, the following assumptions are made:

1) dependency of voltage across diode on diode current can be expressed as third-order polynomial;
2) base contraction due to the moving of the depletion region boundary is omitted, which resulted in single fixed time constant in the reverse recovery;

TABLE IV
LIST OF MODELS BASED ON NUMERICAL AND HYBRID CONCEPT

Model Name	Assumptions	Applicability/comments
Vogler [14] Model, 1992	a. Temperature > 77K b. Boltzmann equation is applicable at the depletion edge	a. Effect of carrier-carrier scattering, Auger recombination, avalanche effects, doping and carrier lifetime profiles are included b. Temperature dependence of the above-mentioned effect is also included in an algebraic expressions c. The use of unphysical effective parameters are avoided d. Self-heating effect is not included This model has very detail consideration of the device physics with very little assumption made. Hence, it is applicable to all types of power diodes of all types of rating, provided self-heating effect is not significant.
Winterheimer [15] Model, 1992	a. Abrupt p+n and n+n junctions b. Carrier lifetime is constant over time c. Steady state forward conduction d. Emitter recombination is neglected e. The excess charge in the swamped zone is approximated by straight line f. The current in the space charge zone is caused by holes only g. The current in the resistance zone is caused by electrons only h. The ratio dn/dx is assumed to be equal to dp/dx in the resistance zone i. Diffusion current of holes in the space charge zone is neglected	a. No fitting parameters are required b. Displacement current at the junction steps is included c. No self-heating is included d. Only turn-off behavior is considered This model is applicable to abrupt pn junction in the study of turn-off behavior.
Goebel [17] Model, 1992	a. Temperature dependence of carrier lifetime is known b. Carriers mobilities are affected by phonon scattering only c. Conduction modulation only affect the resistivity of the lightly doped base region. Its effect on the ambipolar diffusion length is neglected d. Boltzmann equation is applicable at the junction step	a. Self-heating effect is included b. Mobile charge carriers in the space charge region is included c. Velocity saturation effect is included This model can be applied to p-v-n power diodes at temperature range where impurity scattering is not significant. It can also be used to study the transient behavior of power diode under non-steady state turn-on and off conditions. However, the temperature dependence of carrier lifetime needs to be determined experimentally to use the model.

3) charge at the end of phase 1 of the reverse recovery (i.e., at $I_R = I_R M$) is zero, implying a slow di_R/dt, as mentioned by Tseng [12].

The accuracy of the simulation depends on the accuracy of the polynomial approximation, which depends on the measurement data. Thus, the model applies to a specific diode under a specific circuit condition.

D. Summary of Review

From the review of the diode models, a summary table is constructed (Table V) to assist power circuit designers and device designers in the selection of the models. Through the model development, one find the importance of end-region recombination and carrier–carrier scattering in high-current device modeling. The significance of the end-region recombination on the forward characteristics of the power diode has been studied by Choo [20]. For high blocking voltage devices, the voltage-dependent reverse recovery is important. For p-v-n diodes, the nonquasi-static nature of the charge distribution should be considered.

From Table V, one can also see that model development for the p-v-n power diode began in 1991. After 1993, the focus on model development shifted to the analytical model, in order to include the physical effect of the power rectifiers.

TABLE V
SUMMARY OF VARIOUS POWER DIODE MODELS

S/No.	Model	Year	Applicabilities													Remarks
			Type of diode			Rating of power diode			DC	Transient	self-heating effect	Simulator type		# of Input Parameters	Availability of parameter Extraction Procedure	
			p-i-n	p-v-n	p+n/n+	low PIV	high PIV	high current				PSPICE	Saber			
	Analytical Model															
1	Liang [8]	1990			x	x				x		x		7	yes	Ramp condition: $I_{RM} < I_f$
2	Lauritzern [2]	1991	x			x				x			x	5	yes	Only reverse recovery
3	Jin [10]	1991	x	x						x			x	4	yes	Only forward recovery
4	Kraus [7]	1992	x	x		x	x	x	x	x	x		x	17	no	
5	Ma [3]	1993	x			x			x	x			x	9	yes	Ramp condition: $I_{RM} < I_f$
6	Ma [4]	1993	x	x		x			x	x			x	6	yes	Ramp condition: $I_{RM} < I_f$
7	Yang [6]	1994			x					x			x	7	no	Only for RG1 reverse recovery
8	Tseng [11]	1994	x	x		x			x	x		x	x	6	no	
9	Analogy [9]	1995	x	x		x	x	x	x	x	x		x	59	no	Assumptions/derivations unknown
10	Strollo [13]	1996	x	x		x	x	x	x	x		x		20	no	Assumptions unknown
11	Ma [5]	1997	x	x		x	x	x	x	x			x	8	yes	
12	Tseng [12]	1997	x	x		x	x			x		x	x	8	no	
	Numerical and Hybrid Model															
13	Vogler [14]	1992	x	x		x	x	x	x	x			x	26	yes	Model was used to simulate hard driven GTO inverter circuits [25]
14	Winternheimer [15,16]	1992			x	x	x			x				6	no	Only reverse recovery
15	Goebel [17,18]	1992	x	x		x	x	x	x	x			x	11	no	
	Empirical Model															
16	Bertha [19]	1993	x	x	x	x	x	x	x	x		x		18	yes	

However, after 1994, the number of published works on the power rectifier dropped to one per year. However, this reduction in the number of published works does not indicate the maturity of the diode model, as many outstanding issues remain unresolved, as will be discussed below.

IV. DISCUSSION

All the power diode models developed so far are only for one-dimensional (1-D) structure. However, as power diodes are mostly of mesa type, the shape, the bevel angle, and passivation type of the junctions may be important in determining the characteristics of the diode.

Three shapes of mesa-type power diodes are generally employed. They are circular, square, and hexagonal. The current and electric field of the noncircular die shape will be nonuniform along the edge of the die. Current crowding might occur at the corners of the die, thus resulting in local heating and local breakdown. The local heating and nonuniform current distribution can affect the forward and reverse recovery. The depletion region width will be nonuniform as the electric field distribution is nonuniform. Hence, the forward and reverse recovery might also be affected. The effect of shape on the transient characteristics has not been studied to the knowledge of the authors.

The effect of bevel angle on the reverse breakdown voltage has been studied by several individuals, such as Baliga [21]. The effect is due mainly to the change in depletion region width at the edge of the die. The local heating and nonuniform current distribution as a result of the nonuniform depletion width can also affect the forward and reverse recovery. The effect of bevel angle on the transient characteristic of power diodes has also not been studied.

Passivation of mesa-type power diodes could be silicon–resin, glass, silicon oxide, or semi-insulating polycrystalline silicon (SIPOS). The silicon–resin, glass, and silicon oxide passivation could trap charges from the p-n junction, thus resulting in the walkout phenomena observed in [22]. Although SIPOS passivation does not have the problem, under high dV/dt, a transient-voltage-induced leakage current will appear due to the time lag between the application of the voltage and the change in resistivity of SIPOS [23]. How different types of passivation will affect the transient characteristic of the power diode remain unknown.

As the switching frequency for the power diode in most applications is increasing, the switching loss becomes important. Because of the presence of t_{fr} and v_{fr}, as well as V_{RM} and I_{RM}, the switching loss can be very high, resulting in the rise of junction temperature during operation. This rise in junction temperature causes the change in diode characteristics in a dynamic nature. More and more cases reported from the field were due to self-heating from the experience of one of the authors. However, very little work has been done in investigating the self-heating effect.

The surge capability is also important in the selection of the power diode. Diode breakdown occurs, even when a surge voltage across the diode was lower than its static breakdown voltage [24]. The surge capability is closely related to the self-heating effect of a power diode. The inclusion of surge capability in the diode model has not been found, although some investigations have been made in this area.

For a high-switching-speed power diode, lifetime killers are added to the base region of the p-v-n diode. The distribution of the killers might not be uniform, as it is depends on the nature of the killers and the method of introduction of the killers. The nonuniform distribution of the killers causes a local variation of the carrier lifetimes and the related parameters. The allowance for the inclusion of spatial variation of lifetime in the model can be found in one model only. This model was developed by Vogler *et al.* [14].

From the above discussion, one can see that modeling of the power diode can no longer be limited to 1-D modeling. Several multidimensional effects and self-heating effect should be considered in order to produce an accurate model.

For the existing models, the implication of the application of the p-i-n model to the p-v-n diode or vice versa is not known. This is important, since most power circuit design engineers do not know the inside of a power diode. The implication of a wrong model should be assessed.

In fact, the lack of information on the structure of the power diode from the point of view of power circuit design engineers suggests a necessity for the collaboration of three parties in power diode modeling in industry. These three parties are the device manufacturers, the device users, and the company that produces the simulator. The absence of any one of these parties will render a model impractical in usage due to either too many unknown parameters needing to be input, or inaccurate results due to the use of a wrong model, or the model is difficult to simulate with the commonly used simulator.

V. Conclusions

About 20 published power diode models were reviewed in this paper. The recent focus on model development has shifted to analytical micromodels, in order to include effects arising from internal device physics. These models can achieve better accuracy over a wide range of operating conditions. Although the rate of publication of papers containing power diode models has been tapering off in the last few years, this does not indicate all outstanding issues have been resolved. These include multidimensional effects, self-heating, and surge characteristics. For the existing models, a summary table has been created to aid power electronic engineers in selecting appropriate models for their applications.

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