MODELLING AND SWITCHING SIMULATION OF GATE TURN-OFF THYRISTOR USING FINITE ELEMENT METHOD

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ABSTRACT

The gate turn-off (GTO) thyristor has the best voltage blocking and current conducting capabilities among all known high power semiconductor switching devices. The switching characteristics of a GTO thyristor are influenced by doping profile, material properties, lifetime and mobility of holes and electrons. Recently, most of the research on GTO thyristor is strictly experimental and has focused on their physical performances. On the other hand, the internal behaviour of GTO thyristor is not well understood. The best accuracy switching waveforms and the internal behaviour of the device can only be addressed by device simulation. Physical models (Poisson equation, drift-diffusion and current-continuity equations) of GTO thyristor are valuable for studying the internal behaviour of the device is used in the simulation. These equations are numerically solved by using finite element method. This project presents the modelling and switching simulation of GTO thyristor device by developing a device simulation software. The software is designed by using MATLAB Graphical User Interface (GUI) development environment. The device model has been developed based on the device structure and operation. The thesis focuses on the study of a comparison between silicon and silicon carbide GTO thyristor in terms of switching time performances and efficiency at the system level.

ABSTRAK

Gate turn-off (GTO) thyristor mempunyai voltan sekatan terbaik dan kemampuan arus pengaliran di antara peranti-peranti pensuisan separa pengalir berkuasa tinggi. Ciri-ciri pensuisan sebuah GTO thyristor dipengaruhi oleh profil doping, sifat-sifat bahan, jangkahayat dan mobility lubang-lubang dan elektron-elektron. Baru-baru ini, sebahagian besar penyelidikan tentang GTO thyristor adalah terhad kepada ujikaji dan hanya tertumpu kepada persembahan fizikal sahaja. Sebaliknya, perilaku dalaman GTO thyristor tidak difahami dengan baik. Ketepatan terbaik gelombang pensuisan dan perilaku dalaman peranti hanya boleh ditangani melalui simulasi peranti. Model-model fizikal (persamaan Poisson, persamaan-persaman hanyutan-resapan dan kesinambungan-arus) GTO thyristor adalah sangat berharga untuk mempelajari perilaku dalaman peranti digunakan dalam simulasi. Persamaan secara berangka diselesaikan dengan menggunakan kaedah elemen terhingga. Projek ini mempersembahkan permodelan dan simulasi pensuisan GTO thyristor dengan membangunkan satu perisian simulasi. Perisian ini direka dengan menggunakan MATLAB Antara Muka Grafik (GUI) persekitaran pembangunan. Model peranti telah dibangunkan berdasarkan struktur peranti dan operasi peranti. Tesis ini memfokuskan kepada penyelidikan antara silicon dan silicon carbide GTO thyristor dari segi perbandingan antara prestasi pensuisan dan kecekapan di peringkat sistem.

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LIST OF SYMBOLS

k_B	Boltzmann's coefficient
α	Curve fitting parameter
N_d	Doping profile
n	Electron
N_A^-	Electron acceptor concentration
τ_n	Electron carrier lifetime
J_n	Electron density
D_n	Electron diffusion constant
N_D^+	Electron donor concentration
μ_n	Electron mobility
ϕ_n	Electron quasi Fermi level
ϕ	Electrostatic potential
q	Elementary charge
p	Hole
τ_p	Hole carrier lifetime
J_p	Hole density
D_p	Hole diffusion constant
μ_p	Hole mobility

ϕ_p	Hole quasi Fermi level
$\mu_{\max}$	Maximum mobility
$\mu_{\min}$	Minimum mobility
μ	Mobility
ε	Permittivity coefficient
R	Recombination rate
N_{ref}	Reference concentration
T	Temperature
n_i	Intrinsic carrier concentration

LIST OF ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
FEM	Finite element method
GTO	Gate turn-off
GUI	Graphical user interface
GUIDE	Graphical user interface development environment
MATLAB	Matrix Laboratory
OS	Operating system
SCRs	Silicon controlled rectifiers
Si	Silicon
SiC	Silicon Carbide
SRH	Shockley-Read-Hall

CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

Power devices are essential components of most electronics devices and systems which used to control the energy transfer of electronics systems. Recently, due to the growing of global interest in energy saving, efficiency is becoming more important in power devices. Therefore, it is very important to develop power devices that have lower loss and higher efficiency.

Power devices are also required to operate over a broad spectrum power level and frequencies (Tolbert et. al, 2005). As shown in Figure 1.1, passage to power levels of up to 10MW still depends on the development of high-voltage gate-turn off (GTO) thyristors (Gorbatyuk, 2008). Being a device in thyristor family, GTO is making a significant impact in power electronics design. A GTO has the best voltage blocking and high current conducting capabilities among all known high power devices. The ability to turn off the current without reversal of the anode to cathode voltage (Cooper and Agarwal, 2002) has evolved new circuits concepts such as self-commutated, pulse-width modulated (PWM), voltage-driven and multi-step converters, and enables the circuits to operate at higher frequency.

Almost all power devices are fabricated using Silicon (Si), but their performances have approached theoretical limits of Si power devices. Si power devices are limited to operation of low switching speed and low blocking voltages by virtue of the physical properties of Si. Hence, in high power applications, which require efficient, the use of Si is restricted. It is necessary to put semiconductors having better properties than Si in practical use. Much of the research efforts is aimed at developing new semiconductor technologies (Silicon Carbide and Gallium Nitride for example) to improve the existing Si technology. At the moment, silicon carbide (SiC) is one of the candidates for the semiconductor technology for innovative power devices that will replace Si devices (Tamaso, 2008). Compared to current power devices made of Si, SiC have wide bandgap, low intrinsic carrier concentration, and high thermal conductivity make it suitable for high-voltage and high-power density applications (Muzykov, 2009).

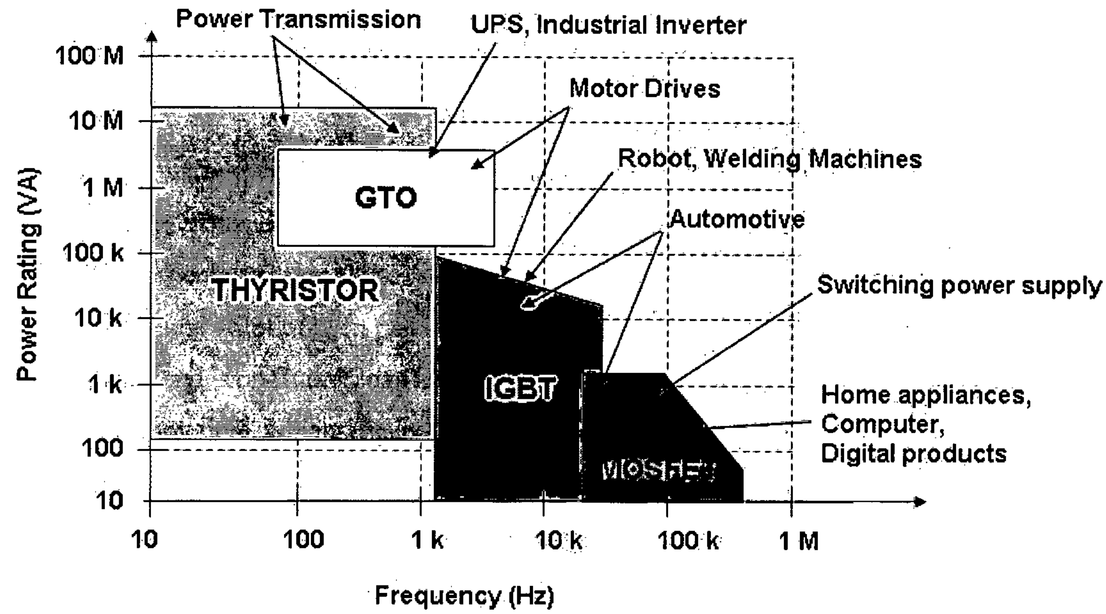

Figure 1.1: Comparison of today's devices application fields and regions of operation.

GTO thyristors with this new semiconductor technology has been experimentally and numerically demonstrated by researchers with different applications. Experimentally, researchers have demonstrated SiC GTO thyristors as the switching devices in circuits driving resistive and inductive loads (Bayne, 2002; Agarwal, 2001; Ryu, 2001). However, internal behaviour of the devices was not examined in-depth. At present, most of the research into SiC GTO thyristors has focused on high forward blocking voltages, but with low forward currents (Bayne, 2002; Cao, 2000). They were not able to produce both high forward blocking voltages and high-on currents on the same device.

In order to analyze the working of the device, a mathematical model is developed to describe the device. While developing the mathematical model, some assumptions are made for simplification. Finally, the governing mathematical expression is developed to describe the behaviour of the device. The mathematical expression usually consists of differential equations and given conditions. These differential equations are usually very difficult to obtain solutions which explain the behaviour of the given circuit system. With the advent of high performance computers, it has become possible to solve such differential equations.

Various numerical solution techniques have been developed and applied to solve numerous engineering problems in order to find their approximate solutions. Especially, the finite element method (FEM) has been one of the major numerical solutions. In particular, any complex shape of problem domain with prescribed conditions can be handled with ease of FEM. The most significant practical advantage is the ability to handle solution domains with arbitrary geometry (Pozrikidis, 2005).

1.2. PROBLEM TO BE ADDRESSED

At present, much of the research being performed with SiC GTO thyristor is strictly experimental (Bayne, 2002; Tripton et. al, 2002; Ryu et. al, 2001) – the device is fabricated, placed into test circuits, and operated until either the tests are completed successful or the device fail. Unfortunately, these experiments can take a significant amount of time and money to set up and they usually do not lend themselves to directly examining what happens within the internal structure of the device. Thus, it can be difficult to determine exactly how a device operates (or fails to operate) through experimentation. At this point, correction has to be made. They can be done by using an appropriate simulation tool. Experimental techniques can do this only approximately and for a few parameters.

Most of the research into SiC GTO thyristor and their limitations have focused on several voltage and current ratings (Yurkov et. al. 2005). Although this device demonstrated reasonable forward blocking voltages, they were not able to produce both high forward blocking voltages and high-on currents on the same device due to its limitations in device fabrication. The results of previous research are only shows for certain amount of voltage which can be applied to the device, otherwise the device would have high losses and less efficient.

Studying performance of power devices, need to visualise the working of devices in a way can be addressed by device simulation. But, professional-level simulators are not particularly accessible in instructional context. They were only available to relatively large commercial engineering concerns. These simulation tools were extremely expensive and in many cases required a large amount of equally training to make effective to use of them. Therefore, a modern simulation tool which more "user-friendly" and ease-to-use need to be developed. The simulation tool also allows you to get up and operational without needing several days or working of training on how to use the tool. However, the tool still requires some fundamental understandings of what you are working with.

A physics-based simulation tool would allow researchers to evaluate semiconductor devices, both new and existing technologies, with less physical experimentation. The researchers would be able to evaluate "what-if" scenario rapidly and see which devices merit further study and which devices require additional design effort. The simulation would also provide full-field and in-depth understanding and show what happen inside the semiconductor devices, which allow the researchers to understand exactly how the devices operate and how they are likely to fail.

1.3. RESEARCH APPROACH

This research utilized the semiconductor physical models of a GTO thyristor and simulates its operation in a circuit test circuit by developing a simulation tool with Si and SiC as the semiconductor materials. The simulation tool was developed to perform physics-based of the GTO thyristor. The primary software used to develop the simulation tool was MATLAB Graphical User Interface Development Environment (GUIDE). GUIDE, the MATLAB GUI development provides a set of tools for creating GUIs. These tools simplify the process of laying out and programming GUIs.

The first phase of this research consisted of developing behaviour and circuit models of a GTO thyristor by using semiconductor transport equations. The equations describe the static and dynamic behaviour of carriers in semiconductors under the influence of external fields that cause deviation from the thermal equilibrium conditions. The equations to be used in the research are as follows: current-continuity equations, Poisson equation, and drift-diffusion equations. Finite element method (FEM) will be implemented in order to solve these equations. This method numerically approximates the solution of the equations by replacing the continuous system with a finite number of non-linear algebraic equations. Final forms of these equations will be used for developing simulation tool by using MATLAB GUI development environment.

The second phase of the research are testing and validating the software. Switching performances of GTO thyristor were validated using a set of voltage and current waveforms that were collected during a previous experimental study of GTO thyristor with SiC semiconductor material (Mookken, 1997). In the switching waveforms validation phase, the circuit condition in the simulation was adjusted to match the switching waveforms of the simulated GTO thyristor to match the experimentally switching waveforms. The validation phase was also used to compare the switching time of the previous experimental study in a circuit operation.

The third and the final phase of the research, the simulation results were used to investigate the switching characteristics of Si and SiC GTO thyristor.

The investigation includes the turn-on and turn-off time and comparison of the performances for both Si and SiC. The simulation results were also used to investigate the inner phenomena of GTO thyristor for both Si and SiC. This step is further verified the switching characteristics of GTO thyristor by correctly simulating the device internal behaviour or inner phenomena of potential, holes and electron distributions during switching time that have been shown in previous GTO thyristor research with SiC material (Shah, 2000). For this part of research project, the simulation file for the physical structure was fixed at each transient time. Each doping layer file of GTO thyristor stored the solutions to the physical models (Poisson's equation, current-continuity equations and drift-diffusion equations) at each point of a specific transient time. This data (potential, holes and electron distributions) was used to investigate the electrical characteristics of GTO thyristor during its switching operation in a circuit.

1.4. RESEARCH OBJECTIVES

The overall goal of this research project is to investigate the switching performances of GTO thyristor. The switching performances should be able to explain, extract and predict the operation of GTO thyristor for variety input gate and anode voltages. The objectives have been divided into three distinct parts – physical characteristics of Si and SiC, switching characteristics of GTO thyristor and development of simulation tool for GTO thyristor.

1.4.1. Physical characteristics of Si and SiC

Physical characteristics for both materials will be investigated through physical models which consisted of semiconductor equations. From the equations, physical characteristics can be modelled by using finite element method. These method is numerically approximate the solution of the semiconductor equations by replacing the continuous system with a finite number coupled linear algebraic equations. The linear algebraic equations used to describe the behaviour of Si and SiC in GTO thyristor lumped with non-linear element into a test circuit.

1.4.2. Switching characteristics of Si GTO and SiC GTO thyristors

Switching characteristics of Si GTO and SiC GTO thyristors will be analyzed in terms of turn-on and turn-off processes. During turn-on and turn-off processes, Si GTO and SiC GTO thyristors are subjected to different voltages across it and different currents through it. The time variations of the voltage across Si GTO and SiC GTO thyristors and the current through them during turn-on and turn-off processes give the dynamic or switching characteristics of Si GTO and SiC GTO thyristors. Here, switching characteristics during turn-on are described and then the switching characteristics during turn-off. Switching time comparison for both Si GTO and SiC GTO thyristor will be explained in-depth.

1.4.3. Development of GTO thyristor simulation tool

The simulation tool to be developed incorporates the device physical models such as Poisson, current-continuity and drift-diffusion equations. Its basic function enables user to investigate GTO switching performances and inner phenomena (potential, hole and electron concentrations) through circuit modification and characteristic observation. Simulation results shall confirm to theoretical and experimental analysis of the device. Besides allowing the user to investigate the device performance, the software will also allow for relatively easy inclusion of the new semiconductor material (SiC). Relatively easy means it can be done by selecting new materials (Si or SiC) and modify the circuit condition to see the effect of the chosen material in terms of switching speed. To facilitate ease of use, the simulator will have a Graphical User Interface (GUI).

1.5. RESEARCH SCOPES

This research will introduce a new physical model of SiC. The investigation of switching performances (turn-on and turn-off) of Si and SiC GTO thyristors will be visualized into two-dimensional (2D) and three-dimensional (3D) plots, through the simulation results including the phenomena inside the device. The physical models has been chosen for GTO thyristor are

i) Poisson's equation

ii) Drift-diffusion equations

iii) Current-continuity equations

To achieve all the research's objectives, knowledge in the following information in necessary

i) Finite element method implementation into the physical models.

ii) Major physical models: drift-diffusion and current-continuity equations, generation-recombination model, mobility model.

iii) Si and SiC physical properties: electron and hole mobility, ionization coefficients, lifetime, intrinsic semiconductor density.

iv) High-level software and development tool: MATLAB Graphical User Interface Development Environment (GUIDE).

1.6. THESIS ORGANIZATION

The remaining chapters of this thesis are organized as follows:

Chapter 2 presents the details of electrical properties and physical characteristics of SiC. GTO thyristor structure and switching characteristics will be discussed briefly. This chapter also discussed the past research of SiC GTO thyristor that provided the foundation for this thesis.

Chapter 3 describes the GTO thyristor structure which to be used in this research project. The semiconductor and drift-diffusion equations to be used in simulation, and the implementation of finite element method in the equations also will be explained in details. This chapter describes the discretization of the equations by using finite element method. Software development approaches, methods taken to validate the results and also discussion on how to implement the equations into programming language will be explained in this chapter.

Chapter 4 presents the discussions on the simulation results. Data from the simulation will be visualized into two-dimensional (2D) and three-dimensional (3D). The results will be presented into a list of data and graph. This chapter also discussed the switching characteristics during turn-on and turn-off states and comparison for both Si and SiC GTO thyristor will be discussed, and inner phenomena of the device will be visualized through three-dimensional plots. Testing and validation of the results shall confirm the theoretical and experimental data from previous work which has been described in **Chapter 2.**

Chapter 5 will summarize the whole thesis and give out some suggestions on future work. The simulation related information and source code listing of the simulator are attached in appendices.

CHAPTER 2

REVIEW OF THE LITERATURE

Before analyzing the switching performances GTO thyristor made from SiC, it is important to know about SiC properties and the device benefits of these properties. In this chapter, an introduction about SiC material will be presented followed by its advantages to the GTO thyristors in terms of switching performances. Past research of GTO thyristors with this material will be discussed in the next section.

2.1. SILICON CARBIDE TECHNOLOGY

An ideal power device should exhibit the following features: carrying any amount of current with zero on-state voltage drop in forward conduction mode, holding off any value of voltage with zero leakage current in the blocking mode, and switching between the on-state and off-state with zero switching time (Elasser, 2002). Practical power devices, however, always exhibit a finite resistance when carrying current in the on-state as well as finite leakage current while operating in the off-state under certain breakdown voltage, both of which lead to power switch (Elasser, 2002). Hence, in reality, the research work on power devices on utilizing advanced materials as well as innovative device structures, or processing techniques to improve the on-resistance, blocking capability and switching time.

Si power devices have served the industry over a long time and they currently dominate power electronics market. Due to inherent limitations of Si material properties, such as narrow bandgap, low thermal conductivity and low breakdown voltage, Si power devices are approaching theoretical limits in terms of higher power and higher temperature operations, offering no significant improvement in device performances with further investment (Chintavali, 2003).

With the development of high quality substrates and processing technologies, 4H-SiC power devices are expected to outperform their Si counterparts in high-power and high-temperature applications, due to the inherent material advantages of 4H-SiC. The material properties of 4H-SiC are listed and compared with other important semiconductor materials in Table 2.1 (Wu, 2009). In comparison to Si, 4H-SiC has the following advantages:

- ✓ The breakdown field is 10 times as high as that Si. For the same voltage rating, 4H-SiC devices can be designed using a much thinner drift region and higher drift doping than that required for their Si counterparts. Thus the specific on-resistance could be significantly reduced, resulting in the much lower conduction power loss and improved power efficiency.

- ✓ As a wide bandgap material, 4H-SiC has a bandgap 3 times as wide as that of Si, which means the current increase due to thermal generation is much lower than Si. In other words, the intrinsic temperature, at which the intrinsic carrier concentration becomes comparable to the doping concentration, is extremely high for SiC devices. Hence, SiC power devices are capable to operate at much higher temperatures, enabling compact power systems with reduced cooling needs. In addition, the wide bandgap of 4H-SiC keeps its power devices from the degradation of electronic properties under high radiation environment such as aerospace.

- ✓ The electron saturation velocity of 4H-SiC is two times than Si. During the switching of diode, the higher electron saturation velocity of 4H-SiC can offer shorter reverse recovery time, as charge stored in the depletion region can be removed faster. Hence, 4H-SiC power devices can be switched at higher frequencies then their Si counterparts.

- ✓ Thermal conductivity of 4H-SiC is three times as high as that Si. As an excellent thermal conductor, 4H-SiC power devices has stronger thermal stability, allowing that heat generated in the power devices to be transmitted to a heatsink and the ambient more easily.

Among the wide bandgap semiconductor materials, SiC materials are by far the most developed for power devices in terms of substrate quality and device processing. According to Table 2.1, diamond is theoretically the best candidate for power devices as it has the highest electric breakdown field, the largest bandgap and the highest thermal conductivity (Wu, 2009). However, its material quality and device fabrication technology are still in its infancy.

Table 2.1 Properties of some important semiconductor.

				Wide Bandgap Semiconductors			
Materials	Si	GaAs	GaN	3H-SiC	4H-SiC	6H-SiC	Diamond
Bandgap Eg (eV)	1.1	1.4	3.39	2.2	3.26	3	5.45
Intrinsic Concentration, n_i (cm^{-3})	$1.5x10^{10}$	$1.8x10^{6}$	$1.9x10^{-10}$	6.9	$8.2x10^{-9}$	$2.3x10^{-6}$	$1.6x10^{-27}$
Dielectric Constant, ε_r	11.8	12.8	9	9.6	10	9.7	5.5
Electron Mobility u_n (cm^2/V-S)	1350	8500	900	900	1140//c	370//c	1900
Breakdown Field, E_c (MV/cm)	0.3	0.4	3.3	1.2	3	2.4	5.6
Electron Mobility Saturation Velocity V_{sat} (10^7 cm/s	1	2	2.5	2	2	2	2.7
Thermal Conductivity Ḱ (W/cm-K)	1.5	0.5	1.3	4.9	4.9	4.9	20
Direct/Indirect	Indirect	Direct	Direct	Indirect	Indirect	Indirect	Indirect

SiC occurs in more than 170 polytypes (which are different crystal structures with the same stoichiometry of a compound semiconductor). Only the

6H-SiC and 4H-SiC polytypes are available commercially in both bulk wafers and custom epitaxial layers (Elasser, 2002). The most suitable and established SiC polytype for high temperature power electronics is the hexagonal 4H polytype (Willander, 2006) and has been chosen in the research because of its high carrier mobility and its low dopant ionization energy.

2.2. SILICON CARBIDE GATE TURN OFF THYRISTORS

Gate Turn Off thyristors (commonly referred to simply as GTOs) are solid state device semiconductor switches that are designed for high power switching applications. To date, the GTO thyristor has the highest power rating and the best trade-off between the blocking voltage and the conduction loss of any fully controllable switch. The main advantage over the thyristor is the higher switching speed and the ability to turn off the current without reversal of the anode to cathode voltage (Cooper and Agarwal, 2000).

2.2.1. Physical Structure

Physically, GTO thyristor is a power semiconductor device with three junctions and three terminals, has a four-layered structure that consists of multiple unit cells connected together in parallel. Each unit cell is comprised of alternating layers of n-type and p-type semiconductor material. In many GTO thyristor, the anode electrode is shorted directly to the wide n-base region as shown in Figure 2.1; the anode shorts are typically added to improve the GTO thyristor's turn-off properties (Vineyard, 2009). Anode shorts are incorporated to provide a path for electrons to reach the contact metallisation, without the injection of holes (Galster, 2007). This type of thyristor is suitable for applications that require high-speed switching, but do not need high reverse voltage.

The four-layer structure of a GTO thyristor allows each unit cell to operate like a pair of coupled bipolar junction transistors as shown in Figure 2.2 (Chintavali, 2003). In the off-state, the wide n-base region is able to support a large depletion region, which allows the GTO thyristor to block a significant amount of voltage. In the on-state, the anode current keeps the transistor regions highly saturated which gives the GTO thyristor a low on-state voltage. Furthermore, since the anode current continually regenerates the n-base and p-base currents required to keep the two transistor regions saturated, the GTO thyristor continues to conduct even with no current flowing into its gate terminal (Galster, 2007).

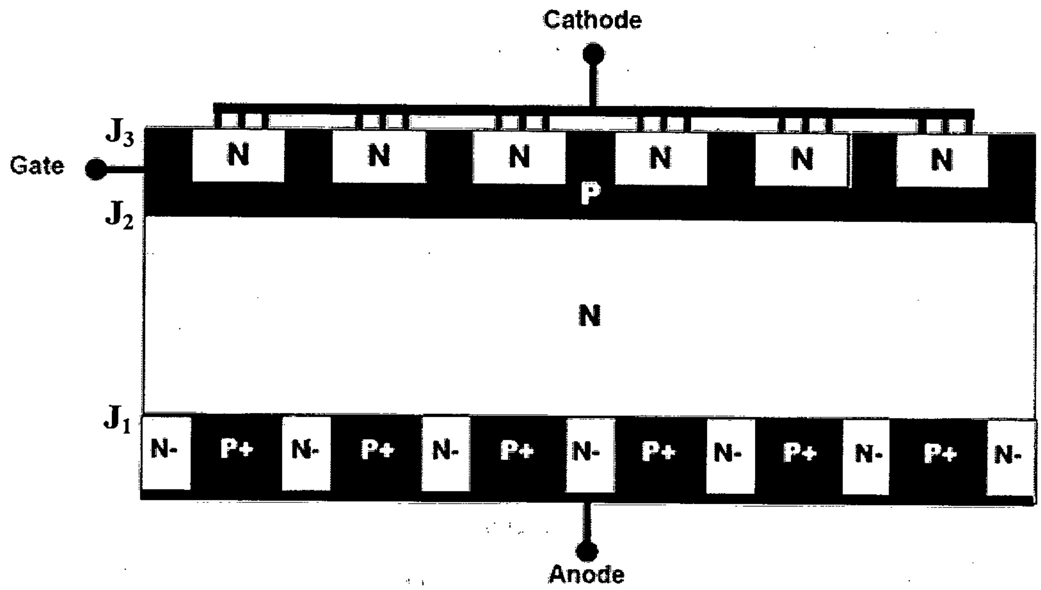

Figure 2.1: Physical structure of a GTO thyristor.

GTO thyristors are current-controlled devices that have two stable operating states, conducting and blocking. Like SCRs, GTO thyristors have excellent voltage blocking and current conducting capabilities and, as described above, do not require a continuous gate current to remain in the conducting state. In the blocking state, the base currents for the transistor regions in each unit cell of the GTO thyristor are effectively zero and the transistor regions remain in the cutoff mode. In the conducting state, the anode current drives the two transistor regions in each unit cell into saturation and keeps the GTO thristor in the current conducting state, so long as there is sufficient anode current to keep the two transistor regions saturated. The minimum amount of current needed to maintain