UNIVERSITÀ DEGLI STUDI DI TORINO

DIPARTIMENTO DI FISICA

UNIVERSITY OF TURIN

PHYSICS DEPARTMENT

MASTER'S DEGREE THESIS

DEFECTS SPECTROSCOPY IN SILICON DIODES

Candidate: Nicolò Barbero

Supervisor: Prof. Ettore Vittone

Examiner: Dr. Marco Truccato

A thesis submitted in fulfillment of the requirements
for the degree of MSc in Physics

July 2014

CHAPTER 0

INTRODUCTION

Semiconductor devices are a fundamental mean of human development. Everyday needs and exotic researches meet in the field of semiconductors science and technology.

0.1 The semiconductor materials: an overview on their applications

Just to give an idea of its vastness, let us consider some of the sectors that involve a research related to semiconductors: artificial intelligence, bioelectrical engineering, circuit design, communications, computational sciences, condensed matter physics, laser and materials for energy and the environment, microelectronics, nanoelectronics, nanotechnology, photonic, signal processing, space technologies and quantum information science.

Under the economic point of view, the worldwide market potential for semiconductors and related devices in 2000 overtook the 462 billion dollars (Source: Icon Group Ltd.) and the demand is still increasing.

Fig. 0.1 shows the successful trend of the semiconductors industry which overtook the global sales related to the steel industry and it is growing faster than the automobiles and general electronics market. Fig. 0.2 shows the distribution continent by continent of the global sales related to the semiconductors market.

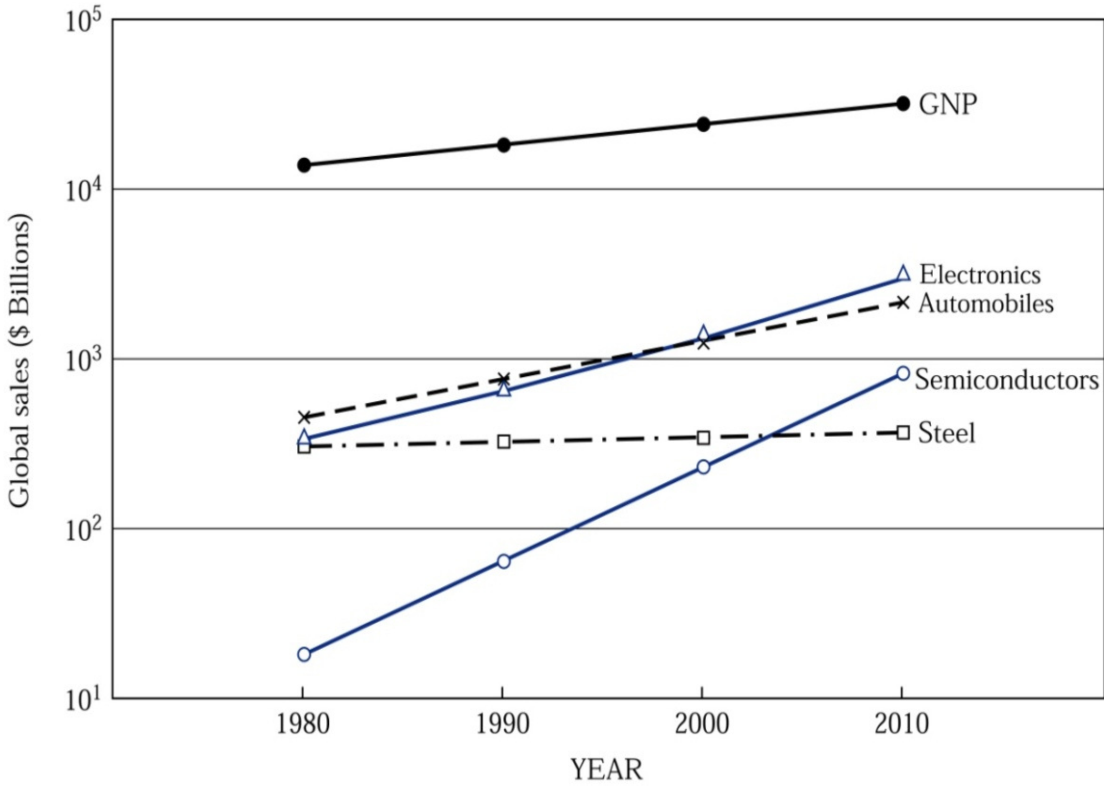

Fig. 0.1 Semiconductors market overtaking other main industrial sectors. Source: [29]

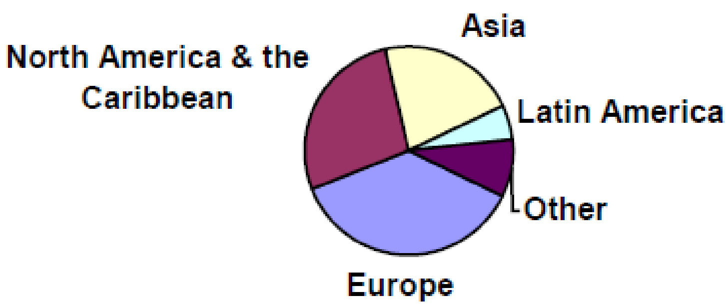

Fig. 0.2. The market of semiconductors in the world

0.2 The semiconductor materials: some current challenges

The challenge of creating faster, smaller and more resistant devices was a starting point for many pathways of innovation. For example a fast recovery time is needed to implement high frequency devices and circuits, the size reduction of devices introduces phenomena closer to quantum world and requires a further knowledge of optical and electrical properties and interaction within the materials, as well as more resistant materials are required for power devices, particle detectors under high fluence, space high radiation exposed setups.

In Fifties solid state devices replaced the vacuum tubes; the industry relied upon silicon bipolar devices, such as bipolar power transistors and thyristors. On one hand the ratings of these devices grew rapidly to serve an ever broader system need but on the other hand they needed a huge and expensive control and protection circuitry to allow them to perform as needed. In Seventies the MOS technology for digital electronics enabled the creation of a new class of devices, including some for power switching applications These silicon power MOSFET have found extensive use in high frequency applications with relatively low operating voltages (below 100 V). MOS and bipolar technology met in the 1980s with the introduction of the Insulated Gate Bipolar Transistor (IGBT). This combination allowed to reach an exotic but extremely efficient device with high power density, simple interface and ruggedness, an ideal choice for most medium and high power applications. An example of this device is shown in Fig. 0.3.

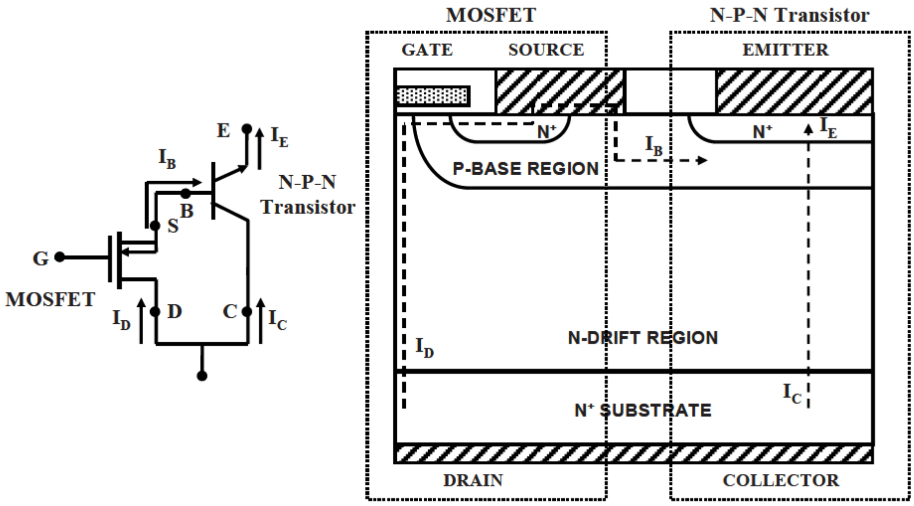

Fig. 0.3. The structure of an IGBT; Source: [31]

Power devices are required for systems that operate over a broad spectrum of power levels and frequencies. They can be classified in two ways, shown respectively in Fig. 0.4 and Fig. 0.5.

From the first graph, it is possible to understand that commonly higher power ratings work at lower frequency and vice versa. The two extreme examples are the microwave oven working at a very high frequency of the order of GHz but at a power of about 100 W. On the other side we High Voltage Direct Current (HVDC) applications, often used to transfer electricity for long distances (powers from the MW to the GW at frequencies of less than 100 Hz). An example is the Desertec project, consisting in the realization of a electricity web all over the Sahara desert.

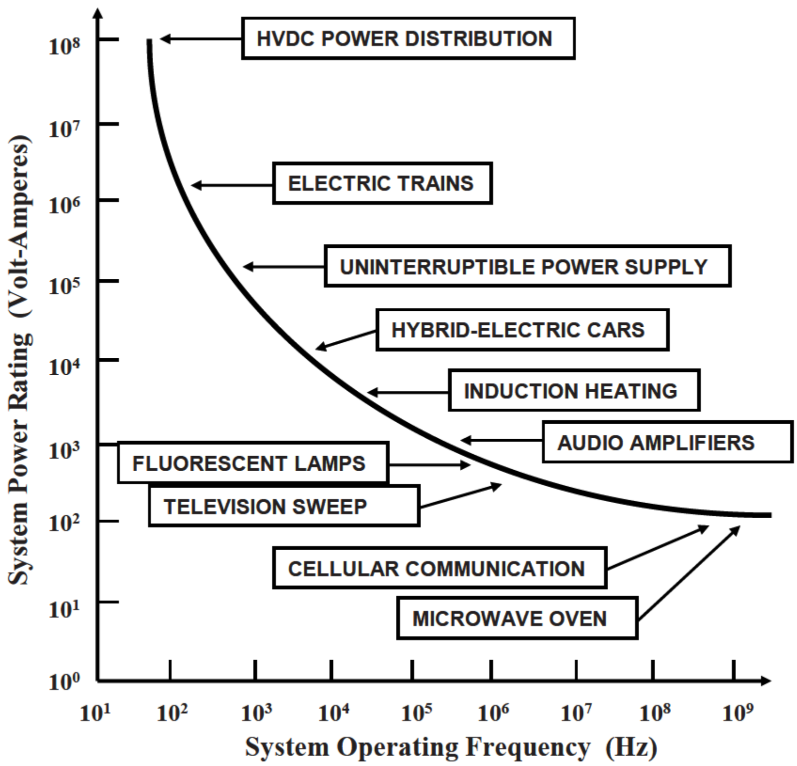

Fig. 0.4. Power devices classification: power rating vs. operating frequency; Source: [31]

The other possible classification is considering the current rating vs. the voltage rating. In this case, the ratings do not follow a precise trend but try to respond to the purpose of the application.

Very complicated circuitry for power applications is based upon few very simple elementary devices, like Schottky rectifiers, PiN diodes, power MOSFETs, bipolar junction transistors, thrystors and IGBT.

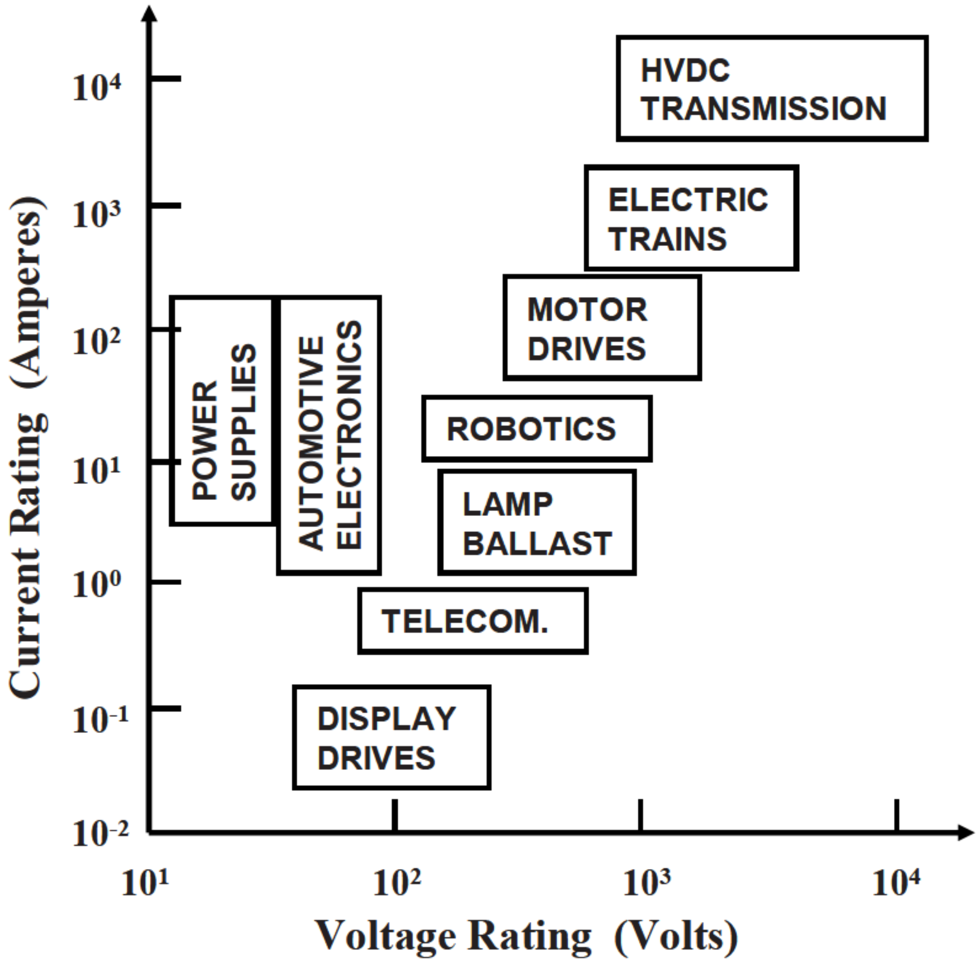

Fig. 0.5. power devices classification: current rating vs. voltage rating; Source: [31]

Their use is not limited to the everyday needs of the society (our domestic fridge, an electric train or for the conversion of energy in an electric farm) but can go beyond and end up in the pathways of scientific research. This is what we are going to explain and discuss quantitatively.

0.3 The semiconductor materials: why are studies on their defects so important?

The above mentioned needed qualities (fast recovery time, small size, radiation hardness, …) are strongly influenced by defects. In fact, any interruption in the periodicity (i.e. symmetry) of a structure could have electrical, optical and mechanical effects.

From the point of view of microelectronics, semiconductors technology and advanced nanomaterials, a proper electrical characterization is needed to understand the ability of a material to resist radiation damage; this quality is called radiation hardness and it is determined by how well the microstructure can remove vacancies and interstitial defects in equal numbers dynamically or in general how much energy is needed to create a crystallographic defect that will induce variations in the behavior of the device. A paper published on Science by G. Ackland in 2010 [32] underlines that after several decades of research on the topic, the exact processes by which the radiation damages are induced and behave is poorly understood, and the search for promising materials has been largely heuristic or oriented by economical and practical limits.

There are two targets: to synthesize optimized materials and to find and exploit proper characterization techniques and protocols in order to understand the quality of these materials. If this process of research will be properly done by the scientific community there is the hope that the characterization not only will confirm the quality of the new materials but will allow to understand the mechanism of damage and the effect of damage too, such a way that will suggest further research pathways in the materials science field.

Literature allows anyone to find several new materials and potential candidates; the answer to the question "which will be the best" will come only in some decades so we, as people that are trying to follow the pathways of research, can just give our best to obtain nice results and hope they will really be useful for the future.

0.4 Two types of defects

As we will see thoroughly in the next chapters, two types of defects can be studied: the impurities and the radiation-induced defects.

In both cases, any defect can be represented by a deep-level within the forbidden gap and a proper theoretical background and experimental technique should be developed to understand how this deep-level "works". The presence of impurities, like transition metals (gold, palladium, platinum, …) within semiconductor devices is a technique developed to increase the switching performance of the power devices, changing the minority carrier lifetime.

On the other hand, the radiation-induced defects are microscopic effects related to the radiation-induced damage that can be macroscopically observed in particle detectors and circuitry for space application. There are many fields of research and technology which require the use of electronic materials and devices working in harsh radiation environments, for example, in high energy physics facilities, remote control systems in nuclear reactors, radiation therapy systems, radiation detectors and the aerospace sector. One needs to consider both the immediate effects of radiation induced damage on material and device electrical properties and also the longer term accumulation of damage which can limit its longevity. While the effects of radiation induced defects on properties of semiconducting and insulating materials and devices have been studied for 50 years, there are still significant gaps in the understanding of which types of defects are formed, how they can be detected and their effects on electrical and structural properties.

The motivation of this work is double. On one hand, there is an interest in building a new facility for the defects spectroscopy at the Physics Department of the University of Torino; to test the new setup we started with four PiN silicon diodes produced by Vishay Semiconductors. Some of these samples contained platinum impurities to improve the switching performance of the device. On the other hand, we tried to extend the use of this setup for other samples (irradiated PiN diodes) to contribute to the CRP (Coordinated Research Project) promoted by IAEA (International Atomic Energy Agency) aiming at the study of radiation induced damage, whose title is "Utilization of ion accelerators for studying and modeling of radiation induced defects in semiconductors and insulators". The proposal for a Coordinated Research Project (CRP) reflects the needs of Member States in the domain of radiation effects of electronic materials, with the aim of enhancing the present understanding of the types and effects of the different defects produced using accelerator-based irradiation and measurements combined with theoretical modeling and simulation. The objectives of the CRP are to enhance the capabilities of the interested Member States by facilitating their collective efforts to use accelerator-based light and heavy ion irradiation of electronic materials in conjunction with all available advanced characterization techniques to gain a deeper understanding of how different types of radiation influences the short and long term electronic properties of materials and devices, leading to an improved radiation resistance.

As shown in Fig. 0.6, the project involves several Institutes all over the world and aims at characterizing by means of several techniques (IBIC, DLTS, CV, Raman, α Spectroscopy, …) some simple semiconductors devices (starting with diodes) before and after the irradiation with MeV ion beams trying to model the damaging phenomena within the materials.

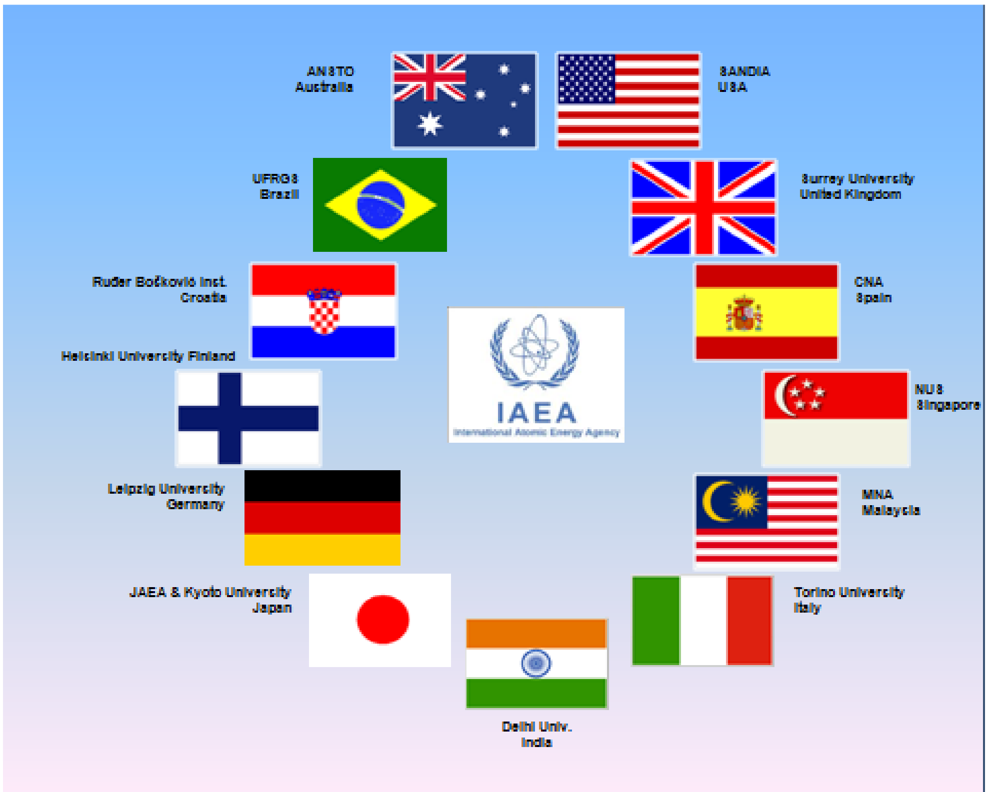

Fig. 0.6. The Institutes and Countries involved in the IAEA CRP on radiation damage

0.5 The structure of the thesis

The first chapter is devoted to the theoretical background needed to understand how deep-levels work and can be studied. A particular attention is given to the Shockley-Read-Hall theory to describe trapping, generation and recombination centers and to the most exploited technique for the defect spectroscopy, i.e. the DLTS (Deep Level Transient Spectroscopy).

In the second chapter the simplest power silicon devices are introduced and described, i.e. the Schottky and the PiN diodes. Then the samples used in this work are classified and described, dividing them in the first group of the Vishay PiN power diodes with platinum impurities and in the second group of the radiation-damaged PiN diodes (i.e. diodes irradiated with a 3 MeV proton beam at different fluences) produced by the University of Helsinki. This Institute is involved, like the University of Torino, in the IAEA CRP above mentioned. Finally an overview on all the most known types of defects is given.

In the third chapter the setups for DLTS and other related techniques are described. Particular importance is given to the way we built the new setup in Torino. The data (IV, CVT and DLTS) dealing with the first group of samples (the Vishay diodes) are collected and analyzed from both the experiment performed within this work: the first at the RBI Institute in Zagreb and the second at the University of Torino.

The fourth chapter starts with an introduction on the radiation damage mechanism and shows the first results (IV, CVT and DLTS data) achieved performing measurements on the irradiated PiN diodes. Finally some considerations on the data are given in the last part of the chapter.

The final chapter (the fifth) is a conclusion dealing with all this work as a whole.

This is just a small contribution within the world of the research dealing with defects. Very little is known till now and more question mark are there than fixed points. But any effort and attempt done was done with passion and hard work.