

# Chapter 1

## Introduction

### 1.1 Basic Considerations

Silicon technology continues to dominate the semiconductor industry. Numerous breakthroughs have resulted in the ability to produce extremely large scale devices on a single die. Many reliability problems have been solved along the way, but new reliability mechanisms are present in compound semiconductors that are not fully addressed by the methods used to increase reliability in silicon.

The most critical difference between silicon and compound semiconductors is in the properties of the basic materials. Silicon has many advantages, including low defect density, high material strength, and good thermal conduction. On the other hand, compound semiconductors involve a host of different materials with widely different properties. Some can only be produced in thin layers, and must be grown on substrates with different lattice spacing. With the exception of SiGe, none have the low defect density of silicon. Moreover, new reliability problems such as gate sinking and current collapse have emerged for which conventional approaches to reliability are not necessarily effective. A far better understanding of material properties is needed in order to understand reliability and radiation effects in these types of semiconductors.

Many of the device structures involve advanced concepts that are quite different from the comfortable world of bipolar and metal-oxide-semiconductor (MOS) transistors made with silicon. For compound semiconductors, one is immediately forced to deal with heterostructures, quantum confinement, and “2DEG” gas concepts, as well as materials

with different bandgaps and physical properties. It can be difficult to sort through these ideas and determine how the more familiar ideas of reliability apply to such structures.

Considerable progress has been made in the development of compound semiconductors during the last 15 years. Early work concentrated on GaAs MESFET technology, primarily for radio frequency (RF) applications, but more recent emphasis has been on developing other devices and materials that provide even better high-frequency performance. Heterojunction bipolar transistors (HBTs) have been developed that use InP-based or SiGe, with extremely high bandwidth and reduced switching time. This has made it possible to design individual transistors with bandwidths above 500 GHz. There has also been extensive progress in developing RF switching modules, where high-frequency performance and high output power are the main requirements. Applications of compound semiconductors can be divided into three basic areas:

- (1) Low and moderate power logic and analog applications that take advantage of the very high operating frequency provided by compound semiconductors, particularly SiGe and InP.
- (2) RF power modules that require very high power density. Although many such applications can be met using GaAs MESFETs, new materials such as GaN can operate at higher temperature and voltage.
- (3) Optoelectronic devices, particularly LEDs and laser diodes. The development of new materials and fabrication methods has expanded the range of wavelengths for optoelectronics, and this continues to be an active development area.

There are other specialized applications that do not fit within these categories, including those involving high voltage or high temperature.

## **1.2 Some Specific Examples**

Two examples are discussed below that help to establish the context for the material in the book.

### 1.2.1 Reliability of advanced GaN transistors

A recent paper discussed progress in the development of GaN transistors intended for high-power, high-frequency applications as well as high voltage [1]. Figure 1-1 compares the specific on resistance of various GaN devices with their silicon counterparts as a function of breakdown voltage; the dashed lines show theoretical limits for the two materials. The silicon devices are somewhat better than the limiting value, but do not perform as well as the GaN devices. Even at lower voltages, GaN has a clear advantage. At higher voltages, GaN devices provide an on resistance that is more than an order of magnitude lower than those using silicon.

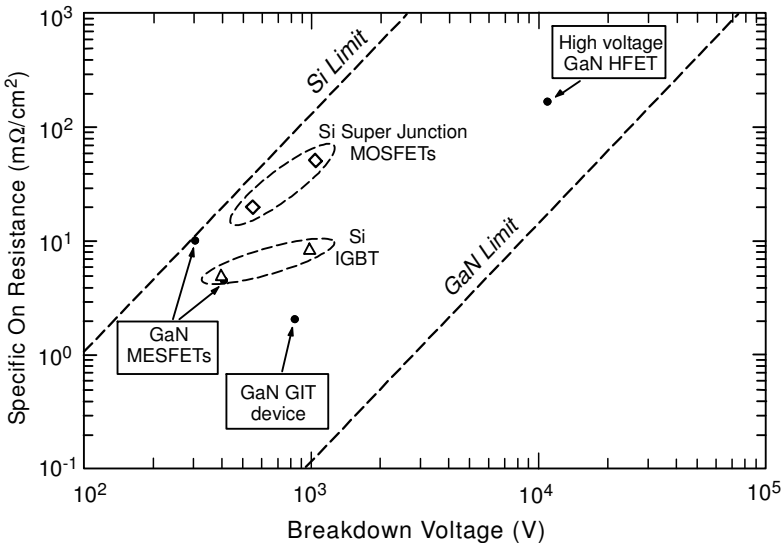


Fig. 1-1. Comparison of various GaN transistors for high-voltage and high-power applications [1]. © IEEE 2008. Reprinted with permission.

Taken at face value, GaN is the obvious choice for applications above 300 V. In addition to lower values of on resistance, the transconductance is higher than for the silicon devices. However, these are complicated devices. The GaN GIT (gate injection transistor) is fabricated on a silicon substrate, which has a different lattice constant. It also has a highly

nonlinear transconductance curve, which could be a problem in some circuit applications.

The high-voltage device, capable of operating at 10,000 V, is fabricated on a sapphire substrate, which also has a lattice mismatch with GaN. This not only affects defect density, but also limits power dissipation because of the low thermal conductivity of sapphire. A new material, AlN, is used as a passivation layer to increase the breakdown strength.

Overall, these are impressive characteristics, but the two devices are not yet in production. A relatively sophisticated knowledge of material and device properties is required in order to determine whether either structure is near the point where it could be produced, or represents just another advance at the laboratory level.

There are several potential reliability issues:

- (1) Both devices use other substrate materials, with different lattice matching.
- (2) Thermal conductivity is much lower for the sapphire substrate, limiting power dissipation.
- (3) The gate structure of the GIT device is new, and it is uncertain how it may affect reliability.
- (4) The properties of AlN are not well known. It was the key breakthrough in achieving the high operating voltage, but could affect reliability.
- (5) The operation of the GaN HEMT depends on extremely thin layers, as well as on the presence of a spontaneous polarization charge. Variations in the properties of the layers could affect unit-to-unit variability, as well as the overall characteristics of the device.

These issues are representative of the types of questions that arise from the body of literature on compound semiconductors. There are many different types of materials, as well as different ways of using them in devices. Their operation, as well as the relevant material properties, must be understood in order to evaluate the work. Due to the limited market for many compound semiconductors, advanced devices are often available only in small production runs, with limited information about reliability. Reliability is usually evaluated with smaller sample sizes and

more limited conditions than for mainstream silicon devices, with the important exception of the cellular telephone industry, which uses large numbers of compound semiconductors.

Highly advanced compound semiconductor devices are used less frequently in space applications. Part of the reason is reluctance by spacecraft designers to use any technology that does not have a record of previous success in space.

GaAs MESFETs are widely used, but they represent an older technology, without the complications of different substrate materials, and have a proven record in many spacecraft. Light-emitting diodes are also widely used, as well as laser diodes.

### ***1.2.2 Radiation damage in light-emitting diodes***

In most cases, compound semiconductors have a relatively high tolerance to radiation damage. They are often accepted for use in space without requiring radiation qualification tests on the basis of “similarity” arguments and cost savings. However, reliability continues to be an important concern, and special burn-in and screening tests are usually required, along with reduced power and voltage limits for circuit applications.

While this approach has generally worked well, there are cases where compound semiconductors have failed in space. In at least two instances the failure effectively ended the mission. One occurred on the NASA Galileo mission, a high-profile mission to explore Jupiter and its moons. The radiation belts of Jupiter are more intense than those surrounding the earth. Radiation damage was a key factor in selecting components for this mission.

The spacecraft, launched in 1989, worked for many years, exceeding its design life by about a factor of two. A total of 34 orbits were made around Jupiter during the explorations phase of the mission. However, the tape recorder\* used for data storage failed during the last orbit. That

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\* It may seem strange that a tape recorder was used. However, the components for the mission were selected in the early 1980s when solid-state memories were limited to about 64 kb per chip.

particular orbit made a closer approach to the planet than the previous 33 orbits, which increased the flux of radiation. The failure was traced to a GaAs LED within the tape recorder electronics package. Operation was temporarily restored afterwards (the annealing approach used for recovery is discussed in Chapter 11).

Laboratory tests were made on similar LEDs shortly after the failure occurred in space. Those results, along with the estimated displacement dose during the Galileo mission, are shown in Fig. 1-2 [2]. During the first 33 orbits the LED output power degraded to about 60% of the pre-irradiation value, with no effect on circuit operation. The high radiation level of the last orbit reduced the light output to about 25%, resulting in circuit failure.

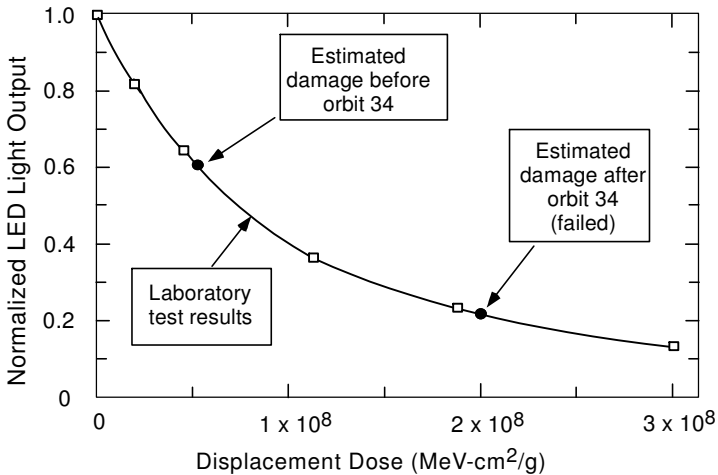


Fig. 1-2. Estimated effect of radiation damage on optical power output from a light-emitting diode in the Galileo spacecraft during the exploration phase around the planet Jupiter.

Despite the high radiation level, this was one of the few electronic or optoelectronic parts that failed during the mission (including many devices fabricated with silicon). A careful series of evaluations and radiation tests had been done on all components used on the spacecraft during the engineering phase.

In the case of the LED, however, the evaluations failed to consider the effects of displacement damage, which causes this particular type of LED to be extremely sensitive to space radiation. We now know that the on-orbit failure could have been avoided by simply using a different type of LED.

This example illustrates the importance of understanding how radiation affects compound semiconductor devices. In retrospect, it is easy to flag this particular LED as a suspect part because of the way in which it constructed. One of the problems with compound semiconductors is the extremely wide range in radiation sensitivity, approximately four orders of magnitude. Although most of them are quite resistant to displacement damage, others are so sensitive that they can fail in space, even in earth-orbiting spacecraft. The key is to understand the device structure and damage mechanisms so that devices that are highly sensitive to radiation damage can be identified.

This brief overview provides some insight into the issues involved for reliability and radiation hardening of compound semiconductors. There are many different types of devices and materials, and only some of the issues relating to them can be discussed in a book of this type. Hopefully the discussion of advanced devices and the underlying physics will allow the book to be useful for many years, even as compound semiconductors continue to advance.

## References

1. N. Tsurumi, *et al.*, “GaN Transistors for Power Switching and High Frequency Applications”, Digest of Papers from the 2008 Compound Semiconductor and Circuits Symposium, pp. 1–5.
2. G. M. Swift, *et al.*, “In-Flight Annealing of Displacement Damage in GaAs LEDs: A Galileo Story”, *IEEE Trans. Nucl. Sci.*, **50**(6), pp. 1991–1997 (2003).