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A review on Silicon Carbide and Gallium Nitride features, reliability and behaviour in the presence of radiations

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***Abstract* - In these years electronics is facing a great change because of the introduction of new materials, i.e. Silicon Carbide (SiC) and Gallium Nitride (GaN). These materials feature great electrical and thermal properties. The current semiconductor solutions have pushed Si and GaAs at their very limits in terms of thermal behavior and efficiency.**

The new semicondcutors, i.e. silicon carbide and gallium nitride, has opened the way to new possibilities and challenges.

In addition, SiC and GaN prove to perform well also in the presence of radiations.

This first part of this review deals with silicon carbide and gallium nitride electrical and thermal features.

The second part deals with GaN behavior in the presence of radiations.

Finally, the third part deals with short and long-term reliability issues of new GaN-based devices.

Keywords: SiC, GaN, reliability, radiation

1. FEATURES OF GaN AND SiC

Silicon carbide semiconductor is a material characterized by a high-energy band-gap, high-critical electric field, high-saturated electron drift velocity and high-thermal conductivity, as shown in table 1.

The excellent material properties of SiC derive from the high strength of the Si-C bond.

SiC exists in a large number of polytypes, the 4H-SiC is the most common for electronic devices because of its overall superior material properties.

SiC devices are typically fabricated on homoepitaxial layers.

They present various fabrication difficulties that are unique among current semiconductors, in particular it is important to guarantee the purity of SiC layers.

It has been observed in [1] and [2], in fact, that there is a positive correlation between defects density and reduced breakdown voltages.

For such difficulties in the production process, SiC devices are still not in mass production, thus, market price of these components is significantly higher than Si counterparts.

Along with silicon carbide also gallium nitride has proved to be a possible future alternative to silicon.

GaN main features are similar to those of silicon carbide. They are:

	Si	**SiC**	**GaN**
Bandgap (eV@300K)	1.12	3.2	3.4
Critical electric field (V/cm)	$2.5 \cdot 10^5$	$2.2 \cdot 10^6$	$3 \cdot 10^6$
Thermal conductivity (W/cmK @300K)	1.5	3-4	1.3
Saturated electron drift velocity (cm/s)	10^7	$2 \cdot 10^7$	$2.5 \cdot 10^7$
Electron Mobility (cm^2/Vs)	1350	950	1000-2000
Hole Mobility (cm^2/Vs)	480	80	30
Dielectric constant	11.9	10	9.5

Table 1. Semiconductors properties

- Operate at high temperature because of a high band gap
- Higher breakdown voltage because of a high band gap
- Low on state resistance because of a high electron mobility
- High switching frequency because of a high electron mobility
- Silicon process compatible with GaN, no expense problems like SiC

In particular, a wide bandgap is important for high temperature operation, chemical inertness and high breakdown voltage.

Up to now, the main technological challenge in gallium nitride production is the synthesis of large area of bulk substrates.

For this reason, nowadays, GaN semiconductors are mainly heteroepitaxial, where the main substrate can be silicon, silicon carbide or sapphire.

A heteroepitaxial structure causes lattice mismatches that can lead to defects in the active layers of the device, such defects deeply affect the device performances in terms of thermal conductivity, critical breakdown field, mobility, carrier concentration and they have a significant impact on the device reliability [3].

A. Comparison between GaN-SiC devices

The typical cross-section of a SiC MOSFET is reported in figure 1.

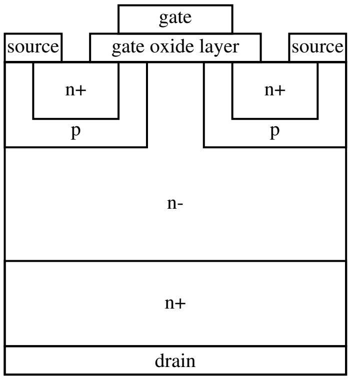

Fig. 1. Cross section of the SiC MOSFET

In SiC MOSFETs, the main challenge to face is the fabrication and the stability of the oxide layer.

The main disadvantage of SiC MOSFETs is the low channel mobility that causes an additional on-state resistance.

This additional on-state resistance is reflected by an increase of the on-state power losses.

A critical aspect for the production of SiC MOSFETs is the reliability and stability of the gate oxide layer, especially for operations over long time at elevated temperatures.

At the moment the SiC MOSFET available on the market are up to 1700V with current ratings up to 160A and on-state resistance of 25-1000 mΩ.

GaN high electron mobility transistors (GaN-HEMTs) for power applications are commercially available from a variety of companies.

These devices features a voltage rated up to 650V and a current of 5-60A.

A typical cross-section of a GaN HEMT is reported in figure 2.

Because of the difficulties in producing large bulk GaN layers, these devices are fabricated in GaN over a Si/SiC substrate.

The heteroepitaxial structure is the main challenge in the production of actual GaN HEMTs since the lattice mismatch may result in a high density of defects in the device layer, thus, resulting in a reduction of the device performance and lifetime.

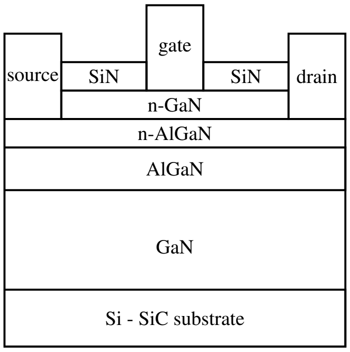

Fig. 2. Cross section of the GaN/AlGaN HEMT

In GaN HEMTs the substrate is typically silicon because it is less expensive than SiC.

The resulting GaN-on-Si structure is a hybrid cascode where the internal silicon body has also the function of the free-wheeling diode, thus, for GaN HEMTs on silicon, there is no need of an external free-wheeling diode.

There are several reasons why gallium nitride semiconductors prove to be of greater interest with respect to silicon carbide semiconductors.

First of all, GaN-based devices' production process shares with silicon the same production technologies.

Therefore, GaN-devices could reach the same prices of Si-based devices, while this does not hold for silicon carbide that shows a great technological challenge in the production process and needs ad-hoc solutions.

Furthermore, GaN has the same thermal and electric properties as SiC, as stated in table 1, which means pushing the limits of actual state-of-the-art semiconductors in terms of size/complexity, cooling and weight even further thanks to a high power, high efficiency, wide bandwidth, high linearity features.

Another important aspect to be considered is the actual and future interest of manufacturers in investing on the GaN and SiC technologies.

Other than in the aerospace-defence and telecommunications, there is great interest in GaN and SiC also in the power electronics and automotive fields.

In these two fields in particular, the lower prices of GaN along with the perspective of a future silicon-comparable price have focused a lot of interest on GaN devices and many different articles are available in the literature, like [4] and [5].

For all these reasons, GaN has faced a rapid technological development, for example, GaN HEMTs are showing a constant increase in their characteristics, i.e. V_{ds} and I_{ds}.

2. RADIATION EFFECTS ON GaN

The technological progress in the aerospace, defense, telecommunications as well as power electronics and automotive fields requires higher and higher powers, voltages and switching frequencies.

Such requirements mean discrete electronic devices with higher blocking voltages but, unfortunately, this also means, for classical semiconductors like Si or GaAs, susceptibility to radiations.

In [6] classical semiconductors behaviour in the presence of radiation has been studied.

As it could be expected, actual commercially available semiconductors are deeply affected by radiation and not suited for operating in an irradiated environment.

The gallium-nitride semiconductor devices prove to perform well also in the presence of radiation.

In [7] and [8], radiation tolerance properties of GaN devices have been tested up to a fluence of 10^{-14}cm^{-2} of 1.8 MeV protons.

The test results show that GaN devices are able to continue to operate normally in presence of ionizing radiations.

On the other hand, in [9] and [10], it has been demonstrated that GaN devices prove to be much more sensitive to displacements due to particle irradiation rather than ionization effects.

The damage caused by the 1.0 MeV protons is higher than the damage caused by the 1.8 MeV protons.

This happens because a non-ionizing radiation has not enough energy to ionize atoms but it has enough energy for excitation.

Therefore, the non-ionizing energy transferred by the incident protons to the atoms in the lattice structure creates vacancies and interstitials.

Annealing can partially recover the degradation effects due to radiation in the gallium sublattice while the nitrogen sublattice is self-healing at room temperature.

For future applications in the aerospace-defense and telecommunications fields, it is of paramount importance to reduce the defects caused by radiation since the long-term reliability is deeply correlated with the presence and density of defects in the layers of the electronic device.

GaN and SiC's thermal properties and radiation hardness are also of great interest for possible applications in highly energetic experiments, [11].

GaN/SiC DC-DC converters could be a suitable power supply for acquisition boards and sensors to be installed at the Large Hadron Collider (LHC) and similar facilities.

In such applications, in fact, the point of load converters have to withstand high levels of radiations, intense magnetic fields and extreme thermal condition due to space limitations and loads characterized by high current drains at low voltages.

3. RELIABILITY OF GaN DEVICES

Field failure rates arise from a variety of causes that need to be identified, contained and eliminated.

The first step to guarantee high-quality and high-reliability GaN devices is at manufacturing level with the screening of the GaN wafer.

The wafer acceptance test (WAT) is a common practice for optimizing manufacturing processes while simultaneously improve reliability, [12].

A typical WAT is shown in figure 3.

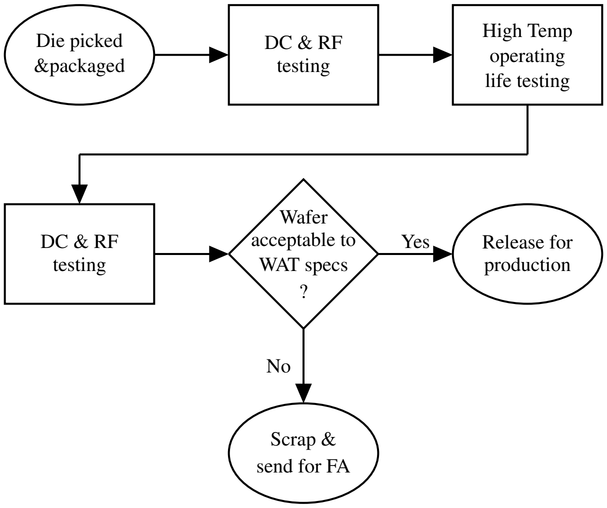

Fig. 3. Wafer acceptance test

The process begins by spatially sampling die across a wafer such that samples are representative of the overall wafer and, then, the die are subjected to DC, RF and high temperature life tests.

Concerning long and short-term reliability, it has been observed that GaN devices follow the well-known bathtub curve.

In [12] it has been show that low voltage products are less affected by early life failures (ELF).

The major causes of failures in GaN are the leakage current and trap-related phenomena, as observed in [13] and [14].

GaN devices suffering early life failures are characterized by a gate leakage current higher than long-life devices.

Therefore, by measuring the gate leakage current, it is possible to identify the sudden-degradation devices.

A critical aspect to be considered in order to limit leakage current is that, in GaN HEMTs, Ni and SiN coexist around the edge of the gate electrode.

Such configuration could lead to the silicidation of the Ni gate edge and to an increase of the gate leakage current.

A protective layer, as proposed in [14], could mitigate the process.

On the other hand, the dislocation and concentration of defects are deeply related to long-term reliability.

Since, typically, degradation arises from the formation of the defects in the AlGaN barrier, a carefully controlled GaN buffer layer could reduce stress degradation, [14].

A n-GaN cap layer can improve the surface morphology and suppress surface oxidation.

It has been discussed whether GaN materials have to follow the Joint Electron Device Engineering Council (JEDEC) standards, [15], or other standards, depending on their application.

The stress conditions on GaN materials are strictly related to the application field, thus, different stress requirements will be needed.

Furthermore, because of the superior electric and thermal properties of GaN, silicon based standard might or might not be sufficient to assess GaN reliability of a given technology.

Therefore, an ad-hoc methodology to assess GaN reliability is necessary.

In [16], a multi-faceted methodology to assess GaN reliability has been proposed.

In figure 4 an overview of the aforementioned multi-faceted reliability methodology is reported.

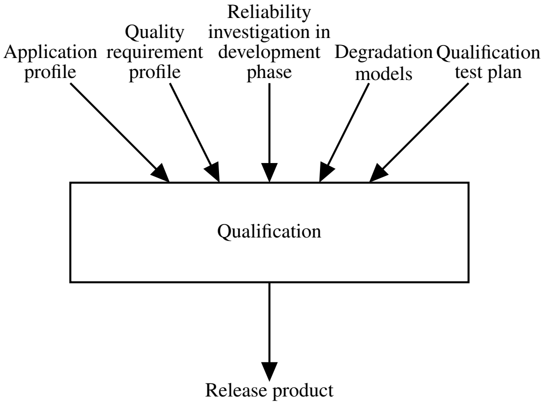

Fig. 4. Multi-faceted reliability methodology

As for classical semiconductors, the thermal behaviour in GaN semiconductors represents a key performance indicator in order to improve the Reliability, Availability, Maintainability and Safety (RAMS) performances.

In addition to that the radiation hardness and magnetic field resistance of GaN means that standard procedures to assess radiation hardness and magnetic field resistance have to be implemented.

The greatest technological challenge in such new reliability procedure is in the design of a measurement set-up able to withstand the hard conditions of the tests to be done.

The measurement set-ups, in fact, have to be immune to intense magnetic field and radiations, otherwise failures in the semiconductor can be induced by an anomalous behaviour, for example spikes in the gate-source voltage of the MOSFET, in the drivers/testing set-up.

4. FUTURE WORK

This work is just a brief overview on SiC and GaN materials. It will be followed by a study of a possible standard procedure for assessing GaN devices' reliability in power electronics applications in ultra-harsh environments.

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