MOTIVATION

It is nowadays difficult to imagine the life without transistors. Transistor is a sort of sandwich made up mainly with Silicon, a dielectric (generally the Silicon native oxide, Silicon dioxide) and a metal. None of our common modern electronic devices would exist without it. No affordable computers, phones, entertainment devices and medical equipment would be available and Internet probably would not exist. But this is not all, since several years, another transformation has begun, with MEMS. MEMS is the acronym of micro-electro-mechanical-system and refers to devices that range in size from the sub micrometer level to the millimetre level, and combines electrical and mechanical components. MEMS extend the fabrication techniques developed for the integration circuit industry to add mechanical elements such as beams, membranes and springs to devices.

This technology was limited during many years to in-house manufacturing or automotive products, such as inkjet print-heads or accelerometers in airbag sensors and it has been more recently applied to a raft of consumer devices and mobiles phones. The most famous examples of devices using such a technology are probably the iPhone from Apple and the Wii from Nintendo. The built-in accelerometer in these devices serves to detect motion and changes in orientation. But an explosion of possible applications is now moving to the industrial and medical instrumentation. With all this panel of new applications, the MEMS market is expected to tremendously grow and any company that is in semiconductors now must do MEMS. In past, the real applications started to exploit the transistor by 20 years after its invention. After 20 years of development the MEMS sector is not in a bad position. The main difference between the semiconductor and MEMS industry is that there has not been a platform MEMS technology on which you can base a number of different devices. Moreover, the industry is still learning, working with different laboratories, to establish a standard process for MEMS, to achieve a level of standardization similar to the CMOS technology in the semiconductor industry.

Transistors and MEMS are currently changing our world. Transistor opened the doors to the computation revolution. MEMS is now part of the evolution, lopening the doors to all about sensors, the sensing revolution. It is sure that transistor and MEMS will continue to drive product research and technological advances we can’t yet even begin to imagine. This is particularly true when imagining new devices with emergent technologies such as Wide Bandgap (WBG) materials, such as Silicon carbide (SiC) and III-nitrides (Gallium nitride, GaN, and Aluminum nitride, AlN), or Carbon-based materials, such as nanotubes and graphene. This will lead to transistors faster than the existing one, more resistant for operation in aggressive ambient, and will lead to computer processors hundred of times faster than the silicon-based products. Up to now, the dominant technology for transistors and MEMS remained the Silicon one, for economical and technical reasons. However, depending on the aimed application, many other materials have superior electrical and mechanical properties relative to Si, such as SiC or GaN. The success of Si electronics is intimately lied to the high quality of insulating layers of silicon dioxide.

But there is now considerable evidence of the need for a semiconductor technology which exceeds the limitations imposed by Si across a wide spectrum of applications. WBG materials, such as SiC and GaN, offer the potential to overcome the harsh environment operation limitation of Si, both for MEMS and transistors devices.

During years, the WBG technology development was limited due to the difficulty in growth and processing of these semiconductors. However, in the past decade, special efforts have been put into the growth and processing aspects of SiC mainly for power devices, and III-nitrides for opto-electronical devices. As a result, the application of such materials both as MEMS or transistors based material has appeared attractive and becomes now clearly realistic.

These materials show no or very low reaction with molecules from the air, thus being a clear advantage respect to Si, for MEMS devices based on surface and small mass loads variation. The high Young's modulus of WBG materials enables them to achieve higher frequencies and quality factors than those obtained with Si resonant devices of identical geometry. The possibility to obtain crystalline or polycrystalline forms also allows to achieve low dissipation layers, thus resulting beneficial in reaching high quality factors.

An important point for WGB MEMS application is the entire compatibility with Si industry. In this sense, it is important to develop a technology fully compatible with the Si one, since Si electronics is still expected to dominate the market for several years. For this, some things are important, the first one being that the process has to be entirely realizable in traditional industrial equipment. This can be easily achieved if the WBG-based device is integrated with Si. In this sense, all the studied WBG resonators presented in this thesis were grown on Si substrate, fully compatible with the traditional Si processes. Moreover, to imagine a possible industrialization of WBG resonators, it is indispensable to dispose of the associated electronics, and thus transistors for eventual circuitry integration, such as the CMOS extensively used at ETSE/CNM [1-7].

Recently, Chung and al. from MIT have reported the first on-wafer integration of Si(100) MOSFETs and AlGaN/GaN HEMTs [8]. This could be an opening way for realizing AlGaN/GaN resonators with Si-integrated circuitry, or why not, with III-nitride circuitry. In fact, III nitrides can also offer piezoelectricity, and in the case of using AlGaN/GaN heterostructures as structural layer, a two-dimensional electron gas (2DEG) is created at the interface, that can be used for actuation/detection.

In such a way, in order to integrate transistor or possible electronic circuitry directly on the structural material of the mechanical part, following the same concept than the successfully Si cantilever integrated with transistors [9], GaN transistors have also attracted our attention. These GaN-based transistors have recently emerged as a possible alternative to the SiC or Si ones. Both GaN metal-oxide-semiconductor and AlGaN/GaN high-electron-mobility transistors (i.e. MOSFETs and HEMTs) could represent a solution for actuation/detection in GaN-based MEMS. Moreover, these devices are also highly interesting for power electronics, and actually the HEMTs ones seem more promising than MOSFETs due to the availability of the 2DEG at the interface.

OUTLINE OF THE THESIS

The attractive physical, electrical and mechanical properties of WBG materials are reviewed in a first part (*Chapter I*). We will see that the high mechanical, thermal, chemical and biochemical stability of the WBG materials enables applications in ambient where Si is limited. Moreover, the high Young modulus of the WBG materials favours their use in high sensitivity applications, such as mass sensors. All these excellent properties render the use of WBG materials very interesting for MEMS fabrication. However, their realization relies on the knowledge of the elastic properties, rupture and fatigue of the thin films materials, such as their internal residual constraint. Since WBG materials are sparse to obtain, compared to Si, it was required to verify the feasibility of such WBG devices.

To achieve this, we have first decided to realize SiC micromechanical devices based on cantilevers and bridges using the SiC/Si heterostructure, using research material from CRHEA (Valbonne, France) and LMI (Lyon, France). Therefore, more details about MEMS and the mechanical behaviour of test structures, which are the base for more complicated devices, are described in *Chapter II*.

Then in the following section, *Chapter III*, a review of the main WBG reported etching techniques is summarized, and we present the first tests performed at CNM. This allowed us to verify the feasibility of SiC and III-nitrides etching with the CNM equipments, but above all to orientate us to establish a first technological process for the realization of beam-based MEMS.

A summary of the realized devices using SiC is then provided in *Chapter IV*, demonstrating the advantages of SiC devices compared with Si. The study begins with the SiC/Si heterostructure as starting material, and follows with the use of SiC on insulated substrate, to avoid electrical leakage problems.

Then in the following parts, III-nitride materials were investigated. In *Chapter V*, AlN on Si was investigated as possible starting material for MEMS fabrication. Electrical measurements motivated us to study this research material as possible dielectric.

Finally, *chapter VI* mainly concerns the first steps realized at CNM into the GaN devices technology, for both MEMS and transistors application. For this, different technological steps such as cleanings, ohmic contacts formation and gate dielectric choice will be studied. The first GaN MOSFETs fabricated at CNM, and AlGaN/GaN HEMTs from CRHEA, will be also presented, compared and measured with temperature.