Progress in Microwave GaN HEMT grown by MBE on Silicon and Smart Cut TM Engineered Substrates for High Power Applications

H. Larhèche [1], B. Faure [2], C. Richtarch [2], F. Letertre [2] , R. Langer [1], P. Bove [1]

[1] Picogiga International, Place Marcel Rebuffat, Villejust 91971 Courtaboeuf cedex 7, FRANCE

[2] SOITEC S.A. Parc Technologique des Fontaines F-38926 Crolles cedex, FRANCE

Abstract — **SiCOI (SiC On Insulator) composite substrates obtained by the Smart-Cut ™ process are alternative possible substrates for epitaxial growth of Wide Band Gap (WBG) materials such as GaN and GaN alloys. Similar to bonded SOI structure, the SiCOI structures basically comprises a thin film of single SiC crystal bonded onto a substrate such as, for instance, silicon substrate. Additionally to the well known insulation properties, SiCOI substrates have been proven to be adapted to the growth of high quality GaN layer. This first study has proven compatibility of SiCOI structure for single layer GaN MBE growth. We present here last results of AlGaN / GaN HEMT structure grown by MBE with NH3 as nitrogen precursor onto SiCOI (on silicon) structure realised by Smart Cut ™. First of all, complete SiCOI structure realisation will be described and typical physical characterization results will be presented for this kind of substrate. Then, will be detailed MBE epitaxy set-up and growth parameters for HEMT structure, including specific buffer layer stack description. Finally, physical and electrical characterisation results for epi-layers and HEMT structure will be presented. Those results show strong compatibility of SiCOI structure for MBE epitaxy of GaN based HEMT structure and demonstrate the interest of Smart Cut ™ approach to build composite substrates, like SiCOI, for hetero-epitaxy application.**

I. Introduction

III-Nitride materials and related devices are clearly identified as a major research field for lighting and high power high frequency applications. Since few years, important progresses have been done for GaN based blue, UV and white LED (Light Emitting Diode), and market for those products is growing really fast. Many promising results have been already published about nitride based high frequency and high power devices, like HFET (Hetero-junction Field Effect Transistor), showing real interest in using nitride base devices for those applications. Nevertheless, many challenges are still across the road leading to optimized devices, and many of those challenges are linked to GaN material quality.

Obtaining high quality low dislocation density GaN material is difficult. High growth rate techniques like HVPE 0 or high pressure high temperature with nitrogen atmosphere and liquid gallium 0 have been used to get low density dislocation GaN substrate, but until now, size of GaN crystal obtained is too small to be used as standard substrate for device realization. Thin film hetero-epitaxy is therefore the most popular way to get GaN based structures. MOCVD and MBE are the most used techniques to grow GaN and alloys thin films onto sapphire, 6H or 4H silicon carbide or silicon (111) substrates. To overcome difficulties of hetero-epitaxy, numerous growth techniques have been developed 0, like use of low temperature AlN or GaN buffer layer onto sapphire substrate for instance. Although those techniques allow realization of GaN based structure compatible with device building, with good final characteristics, material quality improvement is still a major challenge to reach devices with optimized behavior, good reliability and longer lifetime. The use of CSOS (Compound Semiconductor On Silicon) substrate realized by Smart Cut ™ approach can be the next step to reach this goal.

Already recognized for the SOI (Silicon On Insulator) fabrication 0, Smart Cut ™ technology allows to transferred thin film of one material onto another substrate trough molecular bonding interface. The example of homo-substrate (same material for thin film and substrate) like well known bonded SOI demonstrates the potential of Smart Cut ™ technique to produce engineered substrates with specific properties, permitting realization of new high performance devices. Hetero-substrates (different material for thin film and substrate) like CSOS substrates realized be Smart Cut™ may offer an alternative to bulk substrate used for wide band gap material and in particular for III-nitride material epitaxy. The use of CSOS substrate have been already tested for WBG material epitaxy : GaN was grown on Si(111)-On-Insulator 0 with carbonization of Si(111) thin film prior to GaN growth. In this article, we present the use of SiCOI composite substrate, realized by Smart Cut ™ technique, as a substrate for MBE GaN epitaxy.

II Smart Cut ™ SiC-On-Insulator Substrate

SiCOI substrate (SiC On Insulator) is composed of a mono-crystalline SiC thin film handled by a base substrate through an intermediate insulating layer, usually silicon oxyde. Basically, SiCOI structure is built with Smart Cut ™ process. Detailed Smart Cut ™ process applied to SiCOI fabrication has been already described elsewhere 0. It implies high dose hydrogen implantation into a bulk SiC substrate, wafer bonding between implanted SiC substrate and another receiver substrate and finally layer splitting. Wafer bonding is achieved using standard cleaning process and CMP (chemical mechanical polishing) applied to oxidized SiC substrate and/or oxidized receiver substrate. Smart Cut ™ process is compatible with every mono-crystalline SiC polytypes (6H, 4H, 3C). There is also no limitation in term of electrical resistivity and crystal orientation. Thus, either semi-insulating or low resitivity as well as on axis or off axis SiC crystals can be successfully splitted from a bulk substrate and transferred onto a receiver substrate thanks to Smart Cut ™ process. Typical values for the SiC transferred thin film are from 0.2 to 0.8 µm. For buried oxide, thickness is usually comprised between 0.2 and 3 µm. Additionally, Smart Cut ™ technology provides the possibility to use reclaimed SiC substrates, already used for a first transfer. Therefore, it allows to use several times the same SiC donor substrate.

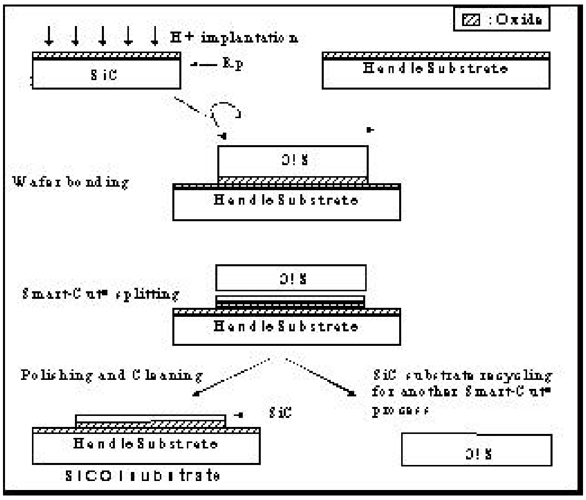

Fig. 1 : Smart Cut ™ process flow schematic (a) and typical picture of SiCOI on silicon (b)

Smart Cut ™ technology allows to use receiver substrate of different nature and size : mainly silicon substrates or poly β-SiC are actually used to realize SiCOI substrates with silicon oxide buried layer. Nevertheless, others kind of receiver substrate or buried layer can be used, depending on final application, like AlN substrate as receiver or silicon nitride as buried layer. This flexibility gives the opportunity to combine advantages of an SiC thin film with a particular substrate through a specific buried layer, which sizes and natures are chosen to bring additional features for the final composite substrate.

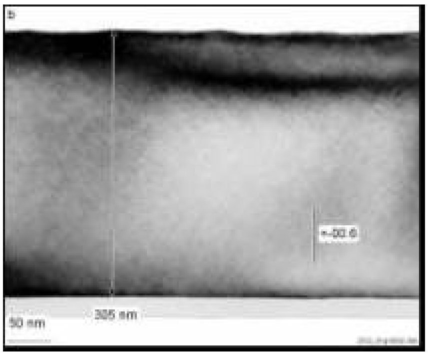

Fig. 2-a: TEM pictures of on axis 6H SiC thin film after Smart Cut ™ process

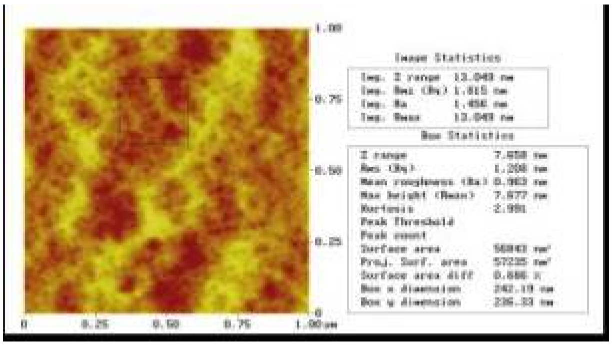

Fig. 3-b: 1x1 µm² AFM picture of on iC thin film surface after Smart Cut ™ process

(a)

SiCOI substrates have been widely characterized for either 6H or 4H thin film transferred onto silicon or poly β-SiC 0. In this particular study, we worked on SiCOI substrate with 300 nm thick on axis 6H SiC thin film on silicon handle substrate with 500 nm thick silicon oxide buried layer. Thin film SiC crystalline quality is conserved after the Smart Cut™ process as seen in

Fig. 3 (a) on the TEM (Transmission Electron Microscope) picture. Typical rocking curve results for SiCOI show a full width at half maximum (FWHM) value around 150 arcsec and confirms TEM results. Surface roughness could be adjusted from 40 to 1,5 ÅRMS thanks to additional polishing steps. 1x1 µm² AFM (atomic force microscope) picture is presented in

Fig. 3 (b), exhibiting a roughness of 18 ÅRMS for final SiCOI surface used as substrate for GaN epitaxy.

III GaN MBE growth onto SiCOI substrate realized by Smart Cut ™

In a previous experiments, 0,7 µm thick GaN layer has been grown by RF plasma assisted Molecular Beam Epitaxy (MBE) technique, exhibiting good structural and physical properties 0. Although this first study have demonstrate the interest in using SiCOI substrate for GaN epitaxy, it necessitates additional experiment to prove the advantage of using SiCOI on silicon for GaN based active structure. The aim of this study is to grow by MBE thicker layers with active structure such as AlGaN / GaN hetero-structure onto SiCOI on silicon composite substrates and evaluate the improvement on structural and electrical characteristics in comparison with similar structure grown on Si(111) substrate.

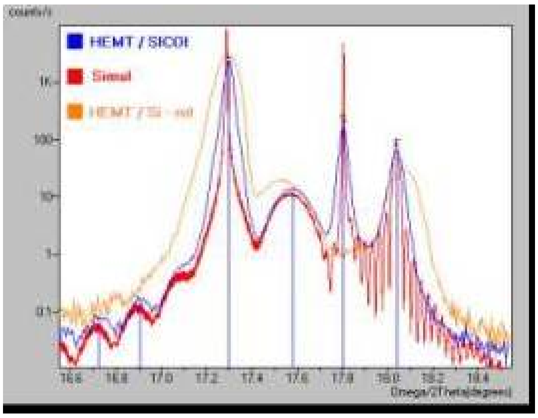

Fig. 4 : XRD measurement results on GaN based structure grown onto Si (111) and SiCOI

The growth process was initially developed on Si (111) substrates 0 and has been adapted to SiC surface. The HEMT structures consist in a 2µm thick AlN / GaN template and a 25 nm thick $Al_{0.30}Ga_{0.70}N$ barrier. It appears that the overall quality of samples deposited on SiCOI is higher than usually observed on Si (111). As observed by X-Ray Diffraction measurements, the FWHM of GaN templates in rocking curve scans drops from 650 arcsec on Si (111) to 140 arcsec on SiCOI. In $\theta/2\theta$ scans, interference fringes arising from AlGaN barrier demonstrates an improvement of interface roughness. It enables also to simulate efficiently the barrier composition and thickness. The results are confirmed by Hall measurements, showing an increase of sheet density for HEMT structure grown onto SiCOI to Si (111) equivalent (Table 1).

Structure	Rsh (ohm.cm)	Ns (cm-3)	µ (cm2/Vs)	Nd template (cm-3)
HEMT / Si (111)	422	9x10[illegible]	1400	3x10[illegible]
HEMT / SiCOI	341	1.10x10[illegible]	1441	1.7x10[illegible]

Table 1 : Hall measurement results on GaN based HEMT structure on Si(111) and SiCOI substrates

VI. CONCLUSION

The use of SiCOI on silicon substrate seems to bring real improvements when used as substrate for HEMT GaN base structure epitaxy, compared with equivalent Si(111) results. In term of III-N quality, no significant difference is observed between layers grown on SiCOI or bulk SiC substrates. Electrical results exhibits same tendency with really good 2DEG characteristics (N_s = 1,2 10^{13} cm^{-3} and μ = 1700 cm²/V.s). This study demonstrates the potential Smart Cut ™ approach to realize new composite substrate like SiCOI on silicon for nitride based hyper frequency and power devices.

REFERENCES

[1] R.P. Vaudo, X. Xu, C. Loria, A.D. Salant, J.S. Flynn, G.R. Brandes : Phys. Stat. Sol. (a) Vol. 194 n°2 (2002), p.494

[2] I. Grzegory, J. Jun, S. Krukowski, S. Porowski, M. Bockowski, and M. Wroblewski, J. Phys.Chem. Solids Vol 56 (1995), p. 639

[3] N.N. Morgan, Y. Zhizhen, X. Yabou : Mat. Sci. And Eng. B Vol. 90 (2002), p. 201

[4] G.G. Shahidi : IBM J. res. & dev. Vol **46,** n°2/3 (March and May 2002)

[5] M.K. Kelly, R. Vaudo, V.M. Phanse, L. Görgens, O. Ambacher, M. Stutzmann : Jpn. J. Appl. Phys. Vol 38 (1999), p. 217

[6] A.J. Steckl, J. Devrajan, C. Tran, R.A. Stall : Appl. Phys. Lett. Vol. 69 n° 15 (1996), p.2264

[7] L. Di Cioccio, F. Letertre, Y. Le Tiec, A.M. Papon, C. Jaussaud, M. Bruel : Mat. Sci. And Eng. B Vol. 46 (1997), p. 349

[8] F. Letertre, J. Brault, G. Feuillet, C. Richtarch, B. Faure, R. Madar, B. Daudin, (Fifth International Conference on Nitride Semiconductor in Nara, 2003)

[9] F. Semond, Y. Cordier, N. Grandjean, F. Natali, B. Damilano, S. Vézian, J. Massies : Phys. Stat. Sol. (a) Vol 188 n° é (2001), p. 501