**RAPPORTO FINALE SUI RISULTATI DEL PROGETTO COMUNE DI RICERCA**
**FINAL REPORT ON RESULTS OF JOINT RESEARCH PROJECT**

**1. Accordo /Agreement**
CNR / PAN
anni/ years 2014-2016

**2. Titolo del progetto**
***ET**erostrutture iNnovative AlGaN/GaN per dispositivi ad Alta efficienza energetica (ETNA)*

**2. Title of the project**
***Energy efficiency Through Novel AlGaN/GaN heterostructures (ETNA)***

Parole chiave (massimo 3)
*Nitruro di Gallio, Elettronica di Potenza, Efficienza Energetica*

Key words (max. 3)
*Gallium Nitride, Power Electronics, Energy Efficiency*

(solo per parte italiana)
Area scientifica / Scientific area (tabella 1/ table1)

*Dipartimento di Scienze Fisiche e Tecnologie dei Materiali*

**3. Responsabili del progetto**
**Project leaders**

| **Responsabile italiano** | **Polish project leader** |
|---|---|
| FABRIZIO ROCCAFORTE | MICHAL LESZCZYNSKI |
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## 4. Obiettivi del progetto

Lo scopo del progetto bilaterale ETNA 2014-2016 è stato lo sviluppo e la caratterizzazione di nuovi processi e di eterostrutture basate su GaN, che possono trovare applicazioni in dispositivi ad alta efficienza energetica. Per raggiungere questo scopo, l'attività di ricerca è stata suddivisa in tre principali obiettivi:

1) Sviluppo di un nuovo processo di crescita selettiva per la realizzazione di dispositivi HEMTs normally-off

2) Studio di eterostrutture basate su GaN su substrati di SiC 2°-off per integrazione monolitica di dispositivi in SiC e GaN

3) Studio di strati di GaN cresciuti su substrati di GaN bulk per la fabbricazione di diodi verticali per applicazioni di alta tensione

I principali risultati dell'attività svolta sono riportati in Sessione 5.

## 4. Aims of the project

The aim of the cooperation project ETNA 2014-2016 was the development and characterization of novel processes and GaN heterostructures, which can find application in energy efficient devices. For this general purpose, the planned activity was divided in three main objectives:

1) Development of a novel p-GaN selective growth process for normally-off HEMTs

2) Study of GaN heterostructures on 2°-off axis SiC for monolithically integration of SiC and GaN devices

3) Study of GaN layers grown onto "bulk" GaN substrates for high-voltage vertical Schottky diodes

The main achievements of the activity are reported in Section 5.

## 5. Risultati ottenuti per obiettivo (1 pagina)
## 5. Achieved results (one page)

### *1) Development of a novel p-GaN selective growth process for normally-off HEMTs*

The comprehension of the p-GaN selective growth process is technologically important to overcome the critical issues of the normally-off HEMTs using the p-GaN gate (e.g., the selective etch of p-GaN). Fig. 1 illustrates schematically the process flow developed by the partners. A $SiO_2$ layer has been used as hard mask for the p-GaN growth. Optical lithography and lift-off processes have been used to define the p-GaN regions. The thickness and uniformity of the p-GaN has been investigated, using different patterns. The results indicated that larger active areas are beneficial to improve the uniformity of the p-GaN layer. Fig. 2 reports AFM and optical images of the selectively grown p-GaN layer. Ti/Al-contacts on the p-GaN layer exhibited an unexpectedly low specific contact resistance of $7\times10^{-4}\Omega cm^2$, suggesting a detrimental role of the geometry and hard-mask "wettability" on the incorporation of p-type Mg dopant .

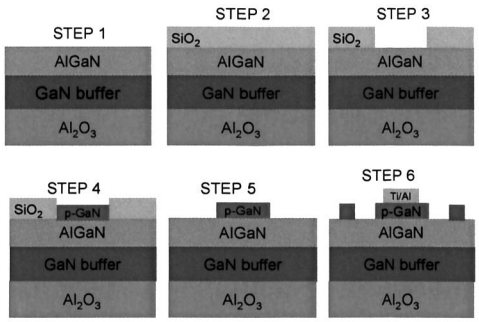


**Fig. 1: Schematic description of the developed p-GaN selective growth process, for normally-off HEMT**

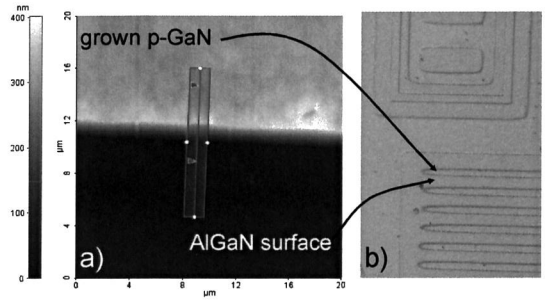


**Fig. 2: AFM analysis (a) and optical image (b) of selectively grown p-GaN regions**

The impact of materials defects on Ohmic contact formed on the AlGaN/GaN heterostructures has been also studied in detail, combining different techniques (HRXRD, AFM, C-AFM, TEM, electrical measurements). The results, summarized in Fig. 3, were object of joint publications.

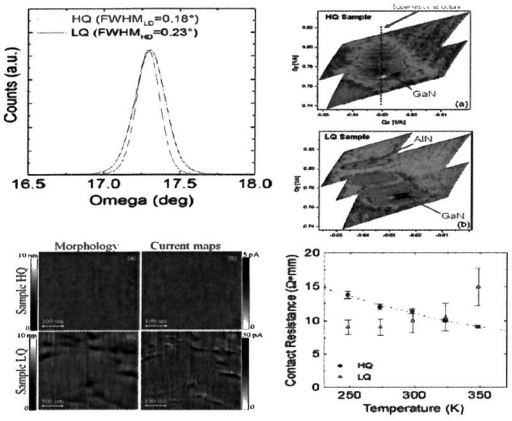


**Fig. 3 : Summary of the characterization performer on heterostructures and Ohmic contacts**

### 2) Study of GaN heterostructures on 2°-off axis SiC for monolithically integration of SiC and GaN devices

Preliminary studies on AlGaN/GaN heterostructures and 2°-off axis 4H-SiC at Unipress and IMM, indicated that the morphology of the AlGaN layers can be improved by employing a SiC lateral patterning (patented at Unipress) to control the step bunching of SiC. Electrical characterization of SiC performed at IMM showed electrical performances of the interfaces, comparable with standard misorientation angles.

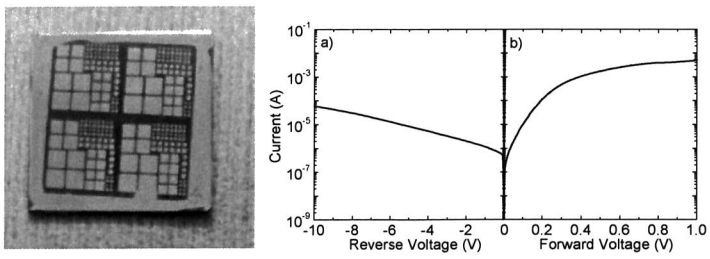


**Fig. 4 : Optical image of the vertical Schottky diodes fabricated on bulk GaN- I-V characteristics of the diodes**

### 3) Study of GaN layers grown onto "bulk" GaN substrates for high-voltage vertical Schottky diodes

Vertical Schottky diodes have been fabricated at IMM on the epilayers grown at Unipress on commercial bulk substrates and electrical characterized. The fabricated diodes, using a Ni Schottky barrier on the front and a Ti/Al-based Ohmic contacts on the back, had an ideality factor of 1.35 and leakage current of $6\times10^{-5}$ A at $V_R$=-10V. The effect of a $SiO_2$ field plate on the reverse characteristics has been investigated with the aim to improve the breakdown voltage. The results pave the way for future activities on vertical bulk GaN devices.

| 6. Prodotti del progetto / Results obtained | |
|---|---|
| | n./no. |
| Pubblicaz. scient. su riviste internaz./ scientific publications on international reviews<br>con IF 2 senza IF 0 | 2 |
| Pubblicaz. in atti congressi internaz./ publications in international congress proceedings | 2 |
| Pubblicazioni in atti congressi nazionali / publications in national congress proceedings | |
| Pubblicazione libri nazionali / Publication of national books | |
| Pubblicazione libri internazionali / Publication of international books | |
| Altre pubblicazioni / other publications | |
| Brevetti / Patents | |
| Prototipi / Prototypes | |
| Strumentazione / Equipment and /or Devices | |
| Programmi software / Software | |
| Banche dati / Data bases | |
| Protocolli / Protocols | |
| Nuovi Materiali / New Materials | |
| Nuovi processi / New processes | 1 |
| Cataloghi/inventari/repertori / Catalogues/Inventories | |
| Atlanti/Carte/Mappe / Atlases/Charts/Maps | |
| Progetti di ricerca / Reserch project | 4 |
| Trasferimento innovazioni / Knowledge transfer | |
| Laboratori congiunti / Joint laboratories | 1 |
| Alta formazione / Training (joint seminars and lectures) | 9 |
| Altro / Other (Oral and poster presentations) | 5 |

**7. Informazioni dettagliate sui risultati indicati sub 6**
**7. Detailed information on results indicated under point 6**

**Scientific publications on international journals: (2)**

- G. Greco, F. Iucolano, C. Bongiorno, F. Giannazzo, M. Krysko, M. Leszczynski, F. Roccaforte, *Ti/Al ohmic contacts on AlGaN/GaN heterostructures with different defect density*, Appl. Surf. Sc. 314 (2014) 546–551, http://dx.doi.org/10.1016/j.apsusc.2014.07.018

- G. Greco, F. Iucolano, C. Bongiorno, S. Di Franco, R. Lo Nigro, F. Giannazzo, P. Prystawko, P. Kruszewski, M. Krysko, E. Grzanka, M. Leszczynski, C. Tudisco, G.G. Condorelli, and F. Roccaforte, *Electrical and structural properties of Ti/Al-based contacts on AlGaN/GaN heterostructures with different quality*, Phys. St. Sol. A, 1–8 (2015), http://dx.doi.org/10.1002/pssa.201431636

**Publications on international congress proceedings : (2)**

- G. Greco, F. Iucolano, C. Bongiorno, S. Di Franco, F. Giannazzo, M. Leszczynski, F. Roccaforte, *Mechanism of Ohmic contact formation in Ti/Al bilayers on AlGaN/GaN heterostructures with a different crystalline quality*, Proc. of the 38th Workshop on Compound Semiconductors Devices and Integrated Circuits (WOCSDICE2014) and 12th Expert Evaluation and Control of Compound Semiconductor Materials and Technology (EXMATEC2014), Delphi (Greece) June 15-18, 2014, pp. 95-96.

- P. Prystawko, P. Kruszewski, M. Ekielski, E. Kaminska, G. Greco, and M. Leszczynski, *MOVPE regrowth of low resistivity non-alloyed ohmic contacts for high performance Nitride HEMT electronic devices*, Proc. of the 16th European Workshop on Metalorganic Vapour Phase Epitaxy (EWMOVPE XVI - 2015), Lund (Sweden) June 7-10, 2015.

**New processes : (1)**

- Process of selective growth of p-type Gallium Nitride (GaN) on AlGaN/GaN heterostructures

**Research projects : (4)**

- FlagEra Joint Transnational Call (JTC) 2015 - **GraNitE - Graphene heterostructures with Nitrides for high frequency Electronics,** *n. 0000141;*
Partners : CNR-IMM (Italy), TopGaN (Poland), CNRS-CHREA (France), STMicroelectronics (Italy).
Project submitted on 27/01/2015, and **approved for funding on 24/09/2015**
Starting date 01/02/2016, duration: 36 months.

- H2020-FETOPEN-2014-2015-RIA Proposal: 685593 – **VeGaN – Vertical Gallium Nitride-based transistors for energy efficient power electronics applications**
Partners: IMEC (Belgium), Ammono (Poland), Institute of High Pressure Physics (Unipress) - PAS (Poland), CNR-IMM (Italy)
Project submitted in March 2015 but not financed.

- H2020-TWINN-2015- CSA -Proposal number: SEP-210272826 - **WideGaP - Strengthening of research abilities of Polish scientific institution involved in the field of wide bandgap semiconductors**
Partners : University of Lodz (Poland), University of Napoli (Italy), Univeristy of Braunschweig (Germany), Acreo (Sweden), CNR-IMM (Italy)
Project submitted in April 2015 but not financed.

- H2020-FTIPilot-2016-1-IA Proposal 760200 - **BLAST - Towards a European value chain for Bulk GaN substrate**
Partners: Lumilog-St.Gobain (France), TopGaN (Poland), STMicroelectronics (Italy), CNR-IMM (Italy), Unipress-PAS (Poland)
Project submitted on 25 October 2016, under evaluation of the experts of EU Commission.

**Joint Laboratory : (1)**

- CNR call for joint laboratories 2015-2017 - **Electronics based on GaN Technologies – LAB (EleGaNT)**
Proposal to Joint Laboratory between the CNR-IMM and the Institute of High Pressure Physics (Unipress)– PAS
Proposal submitted in April 2015 but not financed.

**Training (Joint Seminars and Lectures): (9)**

- Giuseppe Greco (CNR-IMM), *"Ohmic contact and normally-off behaviour: critical issues in new HEMT generation"* (Warsaw, May 29th, 2014);

- Piotr Kruszewski (Unipress – PAS), *"GaN devices at* Unipress*"* (Catania, December 4th, 2014);

- Michał Leszczyński (Unipress – PAS) *"Nitride semiconductor technology in Poland"* (Catania, September, 9th and 11st, 2015);

- Giuseppe Greco (CNR-IMM) *"Characterization of metal/p-GaN interfaces for applications in enhancement mode AlGaN/GaN HEMTs technology"* (Warsaw, September, 17th , 2015);

- Pawel Prystawko (Unipress – PAS), "*Crucial technical issues for selective growth of GaN-based materials"* (Catania, October, 21st, 2015);

- Filippo Giannazzo (CNR-IMM) *"High frequency vertical device based on Graphene and AlGaN/GaN heterostructures"* (Catania, February, 25th, 2016)

- Michał Leszczyński (Unipress – PAS) *"Activity on Gallium Nitride for LED technology carried out at TopGaN (Poland)"* (Catania, February, 25th, 2016);

- Pawel Prystawko (Unipress – PAS), *"Advanced process for non alloyed Ohmic contact on AlGaN/GaN heterostructures based on selected growth technology"* (Catania, February, 25th, 2016);

- Piotr Kruszewski (Unipress – PAS), *"Gallium Nitride and related materials for vertical devices"* (Catania, February, 25th, 2016);

**Other (Oral and poster presentations): (5)**

Oral presentations in international congresses or conferences:

- Giuseppe Greco (CNR-IMM), *Mechanism of Ohmic contact formation in Ti/Al bilayers on AlGaN/GaN heterostructures with a different crystalline quality* WOCSDICE 2014 (Workshop on Compound Semiconductors Devices and Integrated Circuits)–June, $15^{th}$-$18^{th}$, 2014, Delphi, Greece;

- Giuseppe Greco (CNR-IMM), *Characterization of metal/p-GaN interfaces for applications in enhancement mode AlGaN/GaN HEMTs technology* ICSCRM 2015 (International Conference on Silicon Carbide and Related Materials)–October, $4^{th}$-$9^{th}$, 2015, Giardini Naxos, Italy;

- Giuseppe Greco (CNR-IMM) *Role of processing conditions and materials properties on the formation of Ohmic contacts to AlGaN/GaN heterostructures,* EMRS 2016 (European Materials Research Society), fall meeting, symposium G – September, $19^{th}$-$22^{nd}$, 2016, Warsaw, Poland.

Poster presentations at international congresses or conferences:

- Pawel Prystawko (PAS-UNIPRESS), *MOVPE regrowth of low resistivity non-alloyed ohmic contacts for high performance Nitride HEMT electronic devices,* August, $24^{th}$-$29^{th}$, Wroclaw, Poland;

- Giuseppe Greco (CNR-IMM)$^{(*)}$, *Electrical and structural properties of Ti/Al-based contacts on AlGaN/GaN heterostructures with a different quality*, IWN 2014 (International Workshop on Nitrides), Wrocław (Poland) August 24-29,2014.

$^{(*)}$ Presented by Pawel Prystawko

## 8. Formazione di giovani ricercatori
## 8. Training of young researchers

The ETNA project 2014-2016 was extremely fruitful also under the point of view of the formation of young researchers. In particular, the project experience was very useful for the young researcher Giuseppe Greco (CNR-IMM), who had just finished his PhD when the cooperation program started. With this project, he had the possibility to make his first experience at an international level. Practically, during his visits at Unipress, he learnt the basic information on specific structural measurements on AlGaN/GaN heterostructures (i.e., HRXRD, Rocking curves, Reciprocal Space Map Analysis). Moreover, he also had the possibility to familiarize with the concepts of MOCVD (MetalOrganic Chemical Vapour Deposition) reactors used for the p-GaN growth. On the other hand, during the project, the activity on vertical Schottky diodes gave the possibility to the other staff members of CNR-IMM involved in the clean-room devices fabrication (Giuseppe Greco, Fabrizio Roccaforte, Salvatore Di Franco) to acquire important know-how on the processing of this material (the previous experience at CNR-IMM was limited to GaN on sapphire and GaN on Si).
At the same time, the researcher Piotr Kruszewski (Unipress-PAS) could acquire information on the fabrications of Schottky barriers adopted at CNR-IMM as well as on the electrical characterization of the devices.
Since one of the aims of the bilateral programs of CNR is to favor the training of the young researchers and the transfer of knowledge, we would like to have the opportunity to continue our work, already started in the program 2014-2016. Indeed, in the proposal ETNA 2017-2019, a new a young PhD Student and a new Post-Doc will be part of the team of CNR-IMM. In the new proposal for the period 2017-2019, a more intensive exchange of mutual visits is foreseen, with training on the laboratories and bilateral seminars given by the experienced researchers, also in the form of short lectures for the host institution (see preliminary program of the visits of the new proposal). Together with the need to continue the scientific work started during the ETNA program 2014-2016, the above reasons related to the training are at the basis of the request for renewal (2017-2019) that we are going to submit.

**9. Motivazione degli sviluppi della collaborazione negli anni successivi**
(eventuali estensione ad altri paesi, collaborazioni multilaterali, contratti nazionali o internazionali)
**9. Reasons for cooperative project developments in the following years, if any**
(extension to other countries, multilateral collaboration, national or international contracts

CNR-IMM and the Institute of High Pressure Physics (Unipress-PAS) collaborate since 2010, first within the project ENIAC-JU Last Power, thereafter with the CNR-PAS Cooperation Agreement ETNA 2014-2016. This collaboration has been always fruitful in terms of publications and mutual transfer of knowledge.
Clearly, the existing relationship has been strengthened by the present agreement, being a good instrument to continue the cooperation after the end of Last Power project.
During these years, important scientific achievements were obtained (which resulted in joint publications). However, some scientific open issues need still to be solved, which are the basis of the new proposal of research activity for the years 2017-2019 (see section 5 and new proposal). Moreover, a number of initiatives have been carried out to attract new funds and to extend the cooperation network to other European academic and industrial partners operating in the field on GaN materials and devices technology (e.g., CHREA-CNRS, STMicroelectronics, Lumilog-St-Gobain).
In particular, in 2015 CNR-IMM and Unipress-PAS submitted two proposals, i.e., one for a FET-OPEN on bulk GaN vertical devices and the other one for a Joint Laboratory of CNR (see Section 7 for details). Although the proposals were not funded, these initiatives were a driving force which started addressing the research interest activity towards bulk GaN, and left the common intent to re-propose a Joint Laboratory at the next call of CNR. The cooperation project ETNA allowed to extend the relation of CNR-IMM with other Institutions within Poland. As a matter of fact, another Horizon2020 proposal was submitted together with the University of Lodz (see section 7).
Owing to the continuous interaction (possible only thanks to the existence of the ETNA project), these initiatives resulted in 2015 in the approval of the European project FlagEra project GraNiTe (Section 7). The aim of the project will be to explore the integration of graphene layers onto nitrides substrates, for high-frequency devices applications. The project involves the Polish company TopGaN, which is a spin-off of Unipress-PAS. In addition, based on the results achieved within this collaboration, CNR-IMM and Unipress-PAS submitted recently, in October 2016, a Horizon2020 proposal (BLAST) aimed to the development of large area bulk GaN substrates for laser diodes and power devices technologies, involving other industrial partners (see Section 7 for details).
Clearly, all these factors indicate that an extension, to the period 2017-2019, of the cooperation based on mutual visits would be a great opportunity to continue the common research activities on GaN-based technology started with ETNA. In fact, the research on vertical GaN devices will have a significant potential technological impact in the next years in laser diodes and power electronics. Moreover, the possibilities to have another common project (the submitted one, BLAST) and the mutual intention to re-submit a proposal for a Joint Laboratory in the next CNR call represent additional reasons of the importance of the renewal of the project for the period 2017-2019.

(firma del responsabile italiano del progetto)

Dr. Fabrizio Roccaforte (CNR-IMM)

(firma del Direttore CNR-IMM)
Dott. Guglielmo Fortunato

(signature of the project leader)
(anche fax)
Prof. Michał Leszczyński (Unipress-PAS)

Catania, November 22nd, 2016