On-wafer seamless integration of GaN and Si (100) electronics

On-Wafer Seamless Integration of GaN and Si (100) Electronics

Jin Wook Chung, Bin Lu and Tomás Palacios*

Department of Electrical Engineering and Computer Science **and** *Microsystems Technology Laboratories*
Massachusetts Institute of Technology, 77 Massachusetts Ave. Bldg. 39-567B, Cambridge, MA 02139, USA

**Corresponding author; phone: +1-617-324-2395; FAX: +1-617-258-7393; email: tpalacios@mit.edu*

Abstract

The high thermal stability of nitride semiconductors allows for the on-wafer integration of (001) Si CMOS electronics and electronic devices based on these semiconductors. This paper describes the technology developed at MIT to seamlessly integrate GaN and Si transistors in very close proximity (<5 μm). This integration, the first of any III-V field effect transistor with (001) Si electronics, enables tremendous new possibilities to circuit and system designers. For example, we will study the use of hybrid GaN-Si circuits to improve the power distribution networks in Si microprocessors.

Keywords: GaN, high electron mobility transistors, nitride electronics, high frequency, heterogeneous integration.

1. INTRODUCTION

Moore's law has been one of the main drivers behind the unprecedented development of semiconductors in the last forty years. However, this economical and technological paradigm that has helped to create modern Si electronics is now jeopardizing its future. Traditional Si scaling is not only becoming unaffordable, but the performance improvement due to scaling is diminishing.

Our group is working on an approach different from Moore's law to increase the performance of electronics: the heterogeneous integration of different semiconductor materials on the same wafer. In this paper, we describe our work on the seamless integration of GaN-based devices and Si electronics. While Si electronics has shown unsurpassed levels of scaling and circuit complexity, nitride semiconductors offer excellent optoelectronics and high frequency/power electronic properties. The ability to combine these two material systems in the same chip and in extremely close proximity would allow unprecedented flexibility for advanced applications.

2. HETEROGENEOUS INTEGRATION WITH SILICON DIGITAL ELECTRONICS

The unique properties of AlGaN/GaN High Electron Mobility Transistors (HEMTs) have made them the best option for many RF amplifiers. The unsurpassed high current levels possible in these devices [1], in combination with their very high breakdown voltage allow almost 10 times higher maximum power density than GaAs amplifiers [2]. In addition, their high frequency performance, an f_{max} of 300 GHz has recently been demonstrated [3], enables extremely high gain and power added efficiencies. Also, the high output resistance resulting of the small device width significantly simplifies the design of the matching networks in RF amplifiers. Finally, the recent demonstration of device lifetimes in excess of 10^6 hours at a channel temperature of 175C make this technology one of the most reliable semiconductor technologies [4].

In spite of the excellent performance demonstrated by nitride transistors, these devices cannot compete with Si MOSFETs in terms of scalability and level of integration. Modern microprocessors, for example, have more than one billion Si transistors on a single chip [5]. In spite of this unsurpassed scalability, traditional Si electronics is facing tremendous challenges to continue its scaling and performance improvement due to short channel effects and power dissipation. The on-chip integration of nitride and Si technology would enable new flexibility in the circuit and device design to increase the system performance.

Previously, several authors have reported heterogeneous integration of Si and GaAs devices (i.e. field effect transistors, light emitting diodes), by the low-temperature selective epitaxial growth of GaAs on a *miscut* Si(100) substrate [6-8]. With similar technology, several groups have reported the growth of GaN structures on *miscut* Si(100) or Si(110) substrates by molecular beam epitaxy (MBE) [9] and metalorganic vapor phase epitaxy (MOVPE) [10]. However, this approach is challenging because of the difficulty of growing high quality wurtzite GaN on (100)-oriented cubic Si substrates [10]. Moreover, the use of miscut substrates increases the density of surface states in the Si material, degrading the performance of Si electronics designed therein.

The technology to integrate GaN and Si electronics in the same wafer starts by fabricating a virtual Si (001) / GaN / Si (001) substrate by wafer bonding with a SiO_2 bonding interlayer (Fig. 1) [11]. Due to the high thermal stability of GaN, Si CMOS electronics can then be processed in these new substrates without affecting the nitride layers underneath the surface. After the Si devices are fabricated, the Si material is removed from the regions where nitride devices are needed. Then, the nitride devices (transistors, LEDs, lasers or sensors) are processed and, finally, an interconnection layer forms the final hybrid circuits (Figs. 2 and 3).

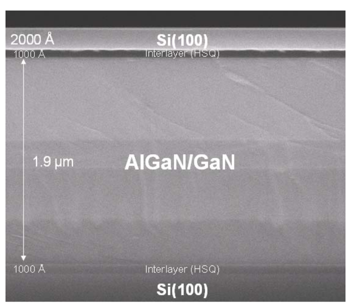


Fig. 1. Scanning electron micrograph of the cross-section of a Si/nitride/Si wafer.

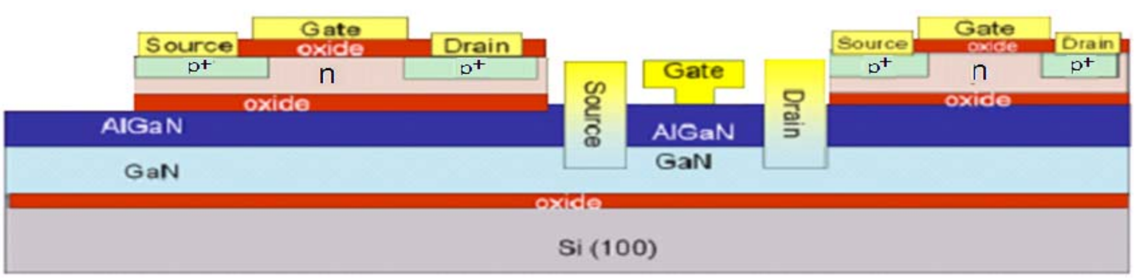


Fig. 2. Diagram showing the cross-section of a virtual wafer with Si pMOS transistors and Nitride HEMTs are fabricated in very close proximity.

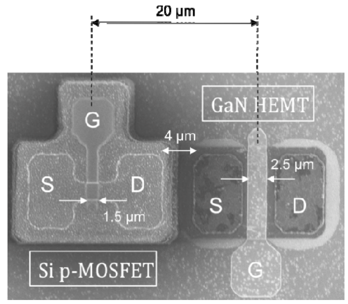
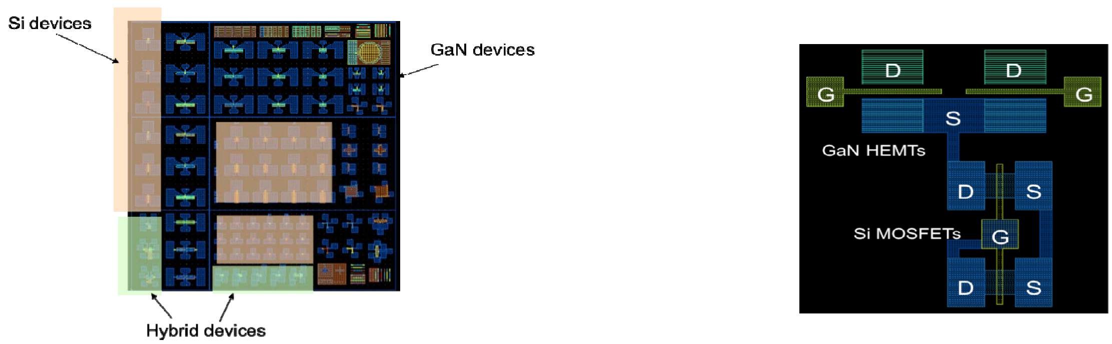


Fig. 3. Scanning electron micrograph of a GaN HEMT and a Si p-MOSFET fabricated side by side in a virtual wafer.



a) b)

Fig. 4. Diagram of the hybrid mask used in this work. Si devices and GaN devices are fabricated at the same time. b) shows the structure of a high power differential amplifier where the GaN devices form the differential pair and the Si MOSFETs act as a current source.

Using this new technology several hybrid circuits are currently being developed, including high power differential amplifiers, normally-off power transistors (Fig. 4) and highly compact DC-DC power converters for advanced power distribution in Si microprocessors.

As an example of the new hybrid GaN-Si circuits currently under developing in our group, Fig. 5 shows the schematic of a GaN-Si hybrid power converter. In this hybrid circuit, switches M1 and M2 see the highest voltage stress and should be implemented with GaN transistors. In the other devices, the voltage stresses are much lower, which allow their implementation with Si electronics. This circuit is currently under fabrication and Fig. 6 shows the simulation results of the circuit described in Fig. 5. The operating frequency was 300 MHz to minimize circuit area. Simulation verifies the excellent behavior of the new design, although additional circuit optimization is needed to improve the efficiency.

3. CONCLUSIONS

Nitride transistors have shown an outstanding improvement in performance during the last few years, which has allowed them to become the first option for power amplification below 10 GHz. However, the range of applications where nitride devices can revolutionize electronics does not stop in power amplifiers. Their high thermal stability allows their seamless integration with Si (100) devices, which enables numerous applications that take advantage of the unsurpassed integration density of Si electronics and the high breakdown and operating frequency of nitrides. This paper has demonstrated the first on-wafer integration of GaN and Si(100) devices and some of the new hybrid circuits allowed by this integration.

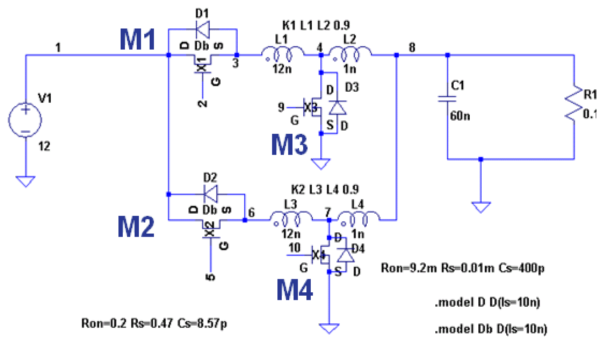


Fig. 5. Circuit schematic of the new GaN-Si hybrid power converter. M1 and M2 are GaN-based power transistors while M3 and M4 are Si MOSFETs.

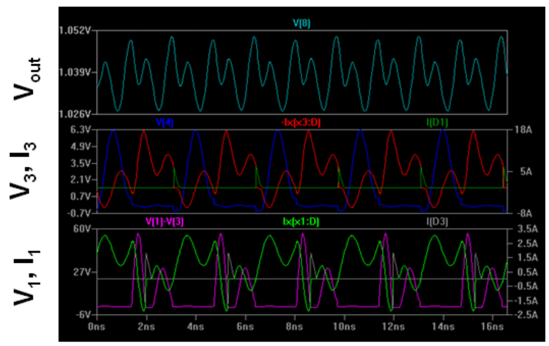


Fig. 6. Simulation of the current and voltage waveforms in the 12:1 V hybrid voltage regulator studied in this project.

4. ACKNOWLEDGEMENTS

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