OBJECTIVE: Develop a commercially relevant tool for activation of implanted dopants for gallium nitride (GaN) and related semiconductor materials and devices at elevated gas pressures with sub-second heating and cooling cycles to achieve dopant activation without decomposition of the GaN surface.

DESCRIPTION: Future Navy ships will require high-power converters for systems such as the rail gun, Air and Missile Defense Radar (AMDR), and propulsion on DDG-51 size ship platforms. High-voltage, high-efficiency power switches are required to achieve the needed power density. Gallium Nitride (GaN) and related III-N alloy materials provide a tunable direct band gap from 0.7 eV to 6.1 eV with high breakdown fields and enable high-power and high-switching frequency devices. In particular, GaN has ~1.5x the breakdown field and ~5x the Balliga Figure-of-Merit compared to SiC, the current state-of-the-art, as well as ~11x and ~850x compared to Si, the current standard. The large Balliga Figure-of-Merit for GaN technology will enable >10kV power switching devices with low on-resistance and high efficiency.

While GaN devices have been commercialized for blue and white LEDs, challenges remain in establishing arbitrary device geometries and doping profiles required for efficient high-voltage and high-frequency devices. Ion implantation is the most versatile approach for the selective area doping required for the efficient high-power devices. However, in GaN materials, high nitrogen decomposition pressure at high temperature (60,000 bar at melt of GaN) causes the surface of the GaN crystal to decompose precluding conventional annealing to activate implanted dopants as employed in silicon and SiC, instead requiring novel annealing methods.

Annealing and activation of the ion implanted p-type magnesium (Mg) dopant in GaN has proven to be more than a 25-year research effort to find an approach that can activate the p-type Mg dopant without decomposition of the GaN surface. Annealing to reduce implant-induced damage requires temperatures near 2/3 the melting point of the crystal or approximately 1,400°C for GaN, whereas the nitrogen begins to leave the GaN surface and decompose the GaN crystal at temperatures less than 900°C at atmospheric pressures. Deposited capping layers allow annealing to 1,100-1,200°C at atmospheric pressures; however, these temperatures are not sufficient to allow activation of implanted p-type Mg dopants in GaN. A combination of ultrafast sub-second heating and cooling cycles and a high nitrogen overpressure is critical to activate implanted p-type Mg dopants in GaN [Refs 1-5].

A novel GaN implant activation approach has been investigated at the Naval Research Laboratory (NRL) [Refs 1-5]. It combines application of moderate nitrogen (N2) overpressure to prevent the GaN surface from decomposing and applying multiple rapid (seconds) heating and cooling temperature pulses above thermodynamic stability of the GaN crystal to accumulate long enough time at high temperatures for the required implant damage reduction processes by diffusion. The approach includes the steps of: (1) a long time annealing regime at temperatures at which the GaN crystal is still stable; (2) transient annealing in the metastable regime using multiple rapid heating/cooling cycles from a baseline temperature to peak temperatures above the thermodynamic stability of the GaN crystal; and (3) a long time annealing regime at temperatures when the GaN crystal is still stable.

The NRL annealing approach made it possible to demonstrate the first GaN p-i-n diode using Mg implantation; however, the GaN sample size is limited to less than 2 inches. Consistency in activation efficiency and implant damage removal remains problematic in the current implementation.

The shortest heating and cooling cycle duration provided by the RF heating in the NRL system is limited to the scale of seconds and heating/cooling rates of 200 K/s. It is the goal of this SBIR effort to develop a system with ultrafast sub-second heating and cooling rates (>1,000 K/s) that allows shorter temperature pulses and thereby achieves higher maximum peak GaN temperatures without the material decomposing. It is much more difficult to achieve sub-second cooling rates than sub-second heating rates, and thus novel cooling approaches should be investigated to achieve the 1,000 K/s cooling rate. In return, the higher peak temperature at each of the multiple heating pulses provides better conditions for diffusional processes in GaN, and results in better restoration of structure damaged by implantation and better activation of the implanted dopants while preserving the integrity of the GaN surface.
The proposed Ultra-Fast Metastable Implant Activation System for Selective Area doping of III-Nitrides should meet the following thresholds:

Deliverable Design Characteristics Value
- Sample size up to 8” diameter, 0.1 to 5 mm thick
- Stabilizing gas (N₂, Ar, H₂, O₂) pressures up to 100 bar
- Primary heating method providing steady heating regime, and heating and cooling rates no less than 1,000 K/s for anneal (50 Bar pressure, baseline temperature ~1,000°C, peak temperature >1,500°C)
- Optional secondary heating method (possibly by laser heating) to exceed 500 K temperature pulse of heating and cooling in less than 100 millisecond (50 Bar pressure, baseline temperature ~1,000°C, peak temperature >1,500°C, mean heating/cooling rate >10,000 K/s)
- Inclusion of windows and ports that would allow process monitoring and control,
- Uniform heating across entire 8-inch wafer with less than 2 percent nonuniformity
- Achieve steady state temperatures up to 2,200°C for potential dopant activation
- Sub-ppb contamination of moisture or gas mixture (e.g., oxygen in nitrogen) inside the chamber
- Successful demonstration of electrical activation of Mg and Si implanted dopants in GaN
- Successful demonstration of maintaining GaN pristine surface integrity for anneals achieving 3 minutes of cumulative time between 1,300°C and 1,400°C

PHASE I: Determine feasibility and establish a plan for the design and development of a system to activate implanted dopants in GaN. Describe features and issues for the design and development of the ultrafast sub-second dopant activation system that can controllably conduct steady-state and transient uniform heating of 8” GaN wafers at required temperatures, heating pulse frequency, and gas pressures up to 100 bar. Ensure that the system is designed to meet all requirements, providing heat treatment regimes necessary for implant activation. Provide a Final Report that convinces that the proposed system can be properly designed to address the above desired and required features and be achieved if Phase II is awarded. Provide a Phase II development plan addressing technical risk reduction.

PHASE II: Develop a fully functional dopant activation system having all parameter monitoring and control tools and capable of producing p/n type conductive regions in GaN and related materials by activating impurities after ion implantation. Demonstrate that the system provides uniform heating of an 8” wafer as required in the technical specification with heating/cooling rates at gas pressures of 50 bar. Deliver a prototype of the fully operational system with appropriate control software to the Navy for evaluation as required by the end of Phase II.

PHASE III DUAL-USE APPLICATIONS: Address the commercialization of the product developed as a prototype in Phase II. Work with suitable industrial partners for this transition to military programs and civilian applications by identifying the expected final state of the technology, its use, and the platform it will be used on. The expected final state of this product will match the requirements given in Phase II and will allow for the tool to be installed, certified, and operated within standards of a modern semiconductor fabrication facility. An implant activation system of this design will enable cost-effective, semiconductor-based, high-power devices for solid-state transformers to replace electromagnetic transformers for the electric grid, rail traction, large-vehicle power systems, and wind turbines.

REFERENCES:


KEYWORDS: GaN; AlGaN; InGaN; III-nitrides; Power Electronics; Wide Bandgap Semiconductor; Electronic Switching Diode; Power Density