Epitaxial growth and properties of wide bandgap *p*-type $NiGa_2O_4$ on β-Ga_2O_3 for high voltage *p-n* heterojunctions with superior performance at elevated temperatures

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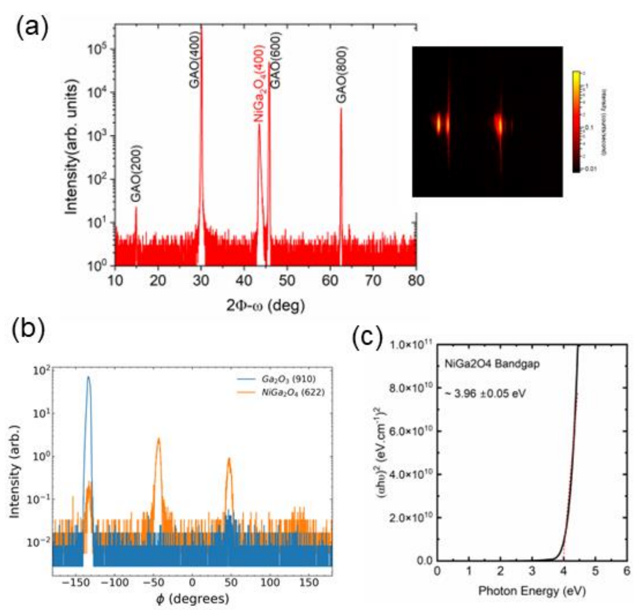
Gallium oxide (β-Ga_2O_3) is a promising wide bandgap oxide semiconductor material with properties well-suited for high power electronics, and recent results show superior high voltage performance compared to the commercial state of the art [1],[2]. Due to the difficulty in the *p*-type doping of Ga_2O_3, unipolar devices based on Ga_2O_3 are prevalent. Several studies have explored bipolar devices using polycrystalline *p*-type oxides such as Nickel oxide and Tin (II) oxide grown on Ga_2O_3 to form heterojunctions[3][4]. However, resulting interface defects and grain boundaries decrease the electrical performance of these devices which directly affects the power device performances, such as breakdown characteristics, on-resistance, and mobility. Hence, the development of high-quality heteroepitaxy of a *p*-type layer with low structural defects on *n*-type Ga_2O_3 is essential to improve device performance in Ga_2O_3-based bipolar devices. For operation at high temperature, thermodynamically stable interfaces are also critical. Recent observations show that $NiGa_2O_4$ forms as a thermodynamical reaction product between Ga_2O_3 and NiO at the p-n heterojunction interface during high temperature operation. Hence the possibility of developing a *p*-type $NiGa_2O_4$ on Ga_2O_3 can circumvent this interface reaction and lead to the development of thermodynamically stable high temperature devices.

In this work, we demonstrate the epitaxial growth of wide bandgap *p*-type $NiGa_2O_4$ thin films on Ga_2O_3 and the device performance of vertical *p-n* heterojunction diodes processed using these heterostructures. Undoped $NiGa_2O_4$ thin films were grown on three different orientations of β-Ga_2O_3 wafers and on a reference Al_2O_3 substrates by pulsed laser deposition. Structural characterizations of the $NiGa_2O_4$ thin films show that 002-oriented $NiGa_2O_4$ grows epitaxially on β-Ga_2O_3 (100) while $NiGa_2O_4$(220) was stabilized on β-Ga_2O_3 (010) orientation. But thin films of $NiGa_2O_4$ grown on Ga_2O_3(001) was polycrystalline. The reflection high energy diffraction (RHEED) patterns during growth were streaky indicating relatively flat surfaces. A bandgap of ~3.95 eV is obtained for $NiGa_2O_4$ thin films from spectroscopic ellipsometry.



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The fabricated $NiGa_2O_4$/β-Ga_2O_3 vertical p-n heterojunction devices demonstrated good specific on-resistance, excellent temperature dependent reverse leakage current and lower on-voltage compared to widely used NiO-Ga_2O_3 heterojunctions. These performances demonstrate that $NiGa_2O_4$/β-Ga_2O_3 p-n heterojunction diodes can be promising for high power devices with low on state power dissipation capable of operating at extreme environments.

Figure 1(a) Wide angle 2theta-omega scan of $NiGa_2O_4$(200) grown on Ga_2O_3(100). Inset shows a 2D frame showing single crystalline growth (b) Phi scan of the $NiGa_2O_4$ and Ga_2O_3 layers (c) Absorption coefficient of $NiGa_2O_4$ thin film obtained from spectroscopic ellipsometry measurement.

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Supplementary Information:

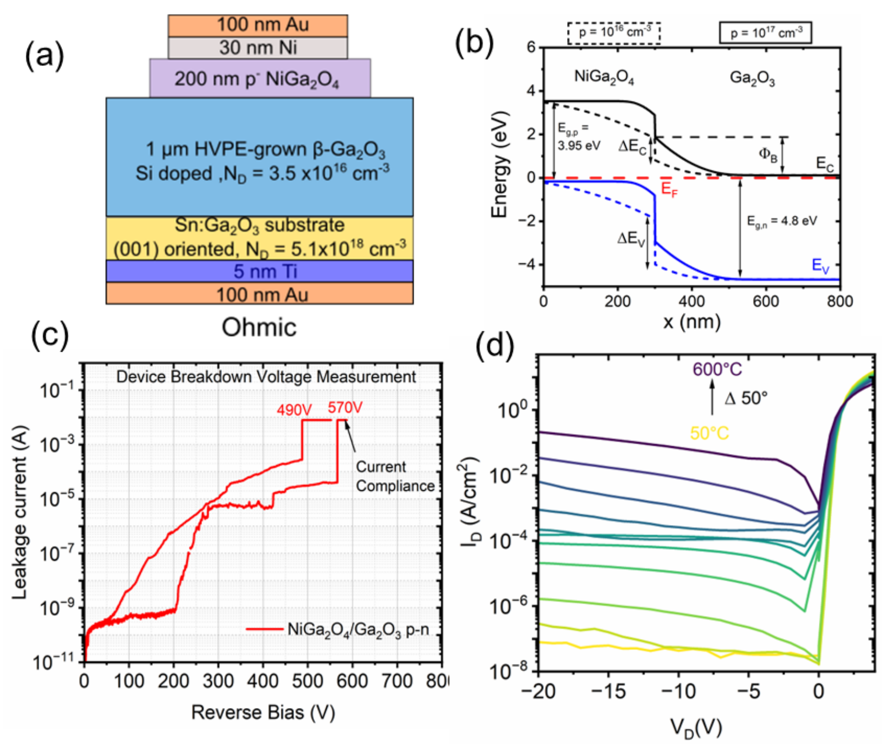

Figure 2(a) Schematic of the device structure for fabricated $NiGa_2O_4$/Ga_2O_3 heterojunction diode (b) Estimated band diagram of the *p*-$NiGa_2O_4$/*n*-Ga_2O_3 junction using values from literature and determined bandgap (c) Room temperature breakdown of two *p*-$NiGa_2O_4$/*n*-Ga_2O_3 diodes (d) Temperature dependent *J-V* characteristics of the diode showing rectification at 600°C operating temperature.