Department of Electrical Engineering, National Tsing Hua University

Special Topic on Implementation Research Report

Investigation on P-Type NiO Thin Films

P 型 NiO 薄膜研究

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Abstract

Gallium oxide (β-Ga2O3) is a promising ultra-wide bandgap semiconductor with outstanding breakdown strength and thermal stability, making it a strong candidate for next-generation power electronics. However, the lack of reliable p-type doping significantly limits its integration into pn junctions and complementary device structures. This study investigates the use of p-type nickel oxide (NiO) thin films as a viable solution, focusing on achieving ohmic contact using Ni/Au metallization. The research explores the effects of oxygen plasma treatment and post-deposition annealing on contact properties, aiming to optimize contact resistance, specific contact resistivity, and film conductivity. Circular Transfer Length Method (CTLM) measurements confirm that moderate annealing temperatures (200°C) and plasma power (100 W) yield the best electrical performance, while excessive treatment leads to contact degradation. These findings lay the groundwork for further electrical characterization through Hall effect measurements to extract carrier concentration and mobility, enabling comparison with β-Ga2O3 and guiding future integration into heterojunction and p-MOSFET devices.

摘要

氧化鎵（β-Ga_2O_3）是一種極具潛力的超寬能隙半導體，具備卓越的擊穿電場強度與熱穩定性，因此被視為下一代功率電子元件的有力候選材料。然而，由於缺乏穩定的 p 型摻雜技術，β-Ga_2O_3在 pn 接面與互補元件結構的應用受到限制。本研究探討使用 p 型氧化鎳（NiO）薄膜作為解決方案的可行性，聚焦於利用 Ni/Au 金屬層實現歐姆接觸。研究中分析氧電漿處理與後製退火對接觸特性的影響，目標在於優化接觸電阻、特定接觸電阻率與薄膜導電性。透過圓形轉移長度法（CTLM）測量發現，適中的退火溫度（200°C）與電漿功率（100 W）可達成最佳電性表現，而過度處理反而導致接觸品質劣化。此結果為後續透過霍爾效應測量載子濃度與遷移率奠定基礎，將可與β-Ga_2O_3進行特性比較，並推動 NiO 在異質接面與 p 通道 MOSFET 元件整合上的應用。

1. Background and Motivation

Gallium oxide (β-Ga_2O_3) is an emerging ultra-wide bandgap semiconductor with excellent thermal and electrical properties, making it ideal for next-generation power devices. However, its lack of p-type doping limits the formation of pn junctions. Nickel oxide (NiO), a wide-bandgap p-type oxide, is considered a promising candidate to complement β-Ga_2O_3, but forming low-resistance ohmic contacts on NiO using Ni/Au metallization remains a major challenge due to Fermi level pinning and low carrier concentration. The research explores the effects of oxygen plasma treatment and post-deposition annealing on contact properties, aiming to optimize contact resistance, specific contact resistivity, and film conductivity.

2. Purpose

This project aims to develop a reliable process to form ohmic contacts on NiO thin films, enabling accurate electrical measurements (e.g., Hall effect) and future integration into p-channel MOSFETs and heterojunction diodes with β-Ga_2O_3.

3. Method

NiO films were formed by RF sputtering and treated with oxygen plasma (100 W, 200 W). Ni/Au (50/100 nm) bilayer contacts were deposited via lithography. Post-deposition annealing was performed in oxygen ambient at 200°C, 250°C, and 300°C. The Circular Transfer Length Method (CTLM) was used to evaluate the contact resistance, sheet resistance, and specific contact resistivity from I-V measurements. Since CTLM has a concentric circular electrode, it avoids the need for lateral isolation and simple fabrication, however a correction factor is needed in CTLM since the current in CTLM flows radially between circular contacts, causing the electric field and current density to vary with radial distance, leading to a nonlinear distribution that affects the effective resistance as illustrated in Fig. 1.

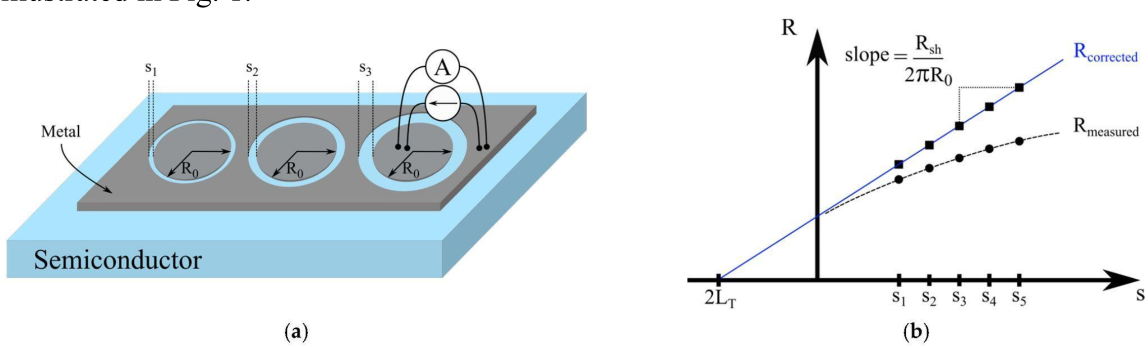

Fig 1: (a) illustrates the CTLM structure, (b) illustrates a CTLM resistance (slanted) and the corrected version (straight) [1]

[1]: Berger C., Alquier D., Michaud J.F. How to Accurately Determine the Ohmic Contact Properties on n-Type 4H-SiC

The correction factor is as below:

$$Cs = \frac{Ro}{s}\ln\left(1 + \frac{s}{Ro}\right)$$

Where Ro is the radius of the inner electrode and s is the spacing between the inner and outer electrodes. The correction factor is then multiplied to the resistance to obtain the real resistance. The total resistance between contacts is as given:

$$R = 2Rc + \frac{Rsh \cdot d}{W}$$

Where R is the measured total resistance, Rc is the contact resistance, Rsh is the sheet resistance, d is the spacing between contacts, and W is the width of the contacts. We can go on to obtain Rsh:

$$Rsh = \frac{dR}{dd} \times W$$

Rc can be calculated by taking the intercept (b) getting:

$$Rc = \frac{b}{2} \times W$$

And specific contact resistance (ρc) can be obtained as:

$$\rho c = Rsh \times \left(\frac{dR}{dd} \times b\right)^2$$

4. Results

Ohmic behavior was confirmed in all non-degraded samples (shown in fig. 2, 3) as shown in fig. 4. Optimal results were obtained with 200°C annealing and 100 W oxygen plasma treatment, achieving a contact resistance of 29.47 Ω·cm, specific contact resistivity of 0.01115 $\Omega\cdot cm^2$ and sheet resistance of 44.595 Ω/sq. Excessive treatment (>270°C or 200 W plasma) degraded contact performance due to gold delamination or interface over-oxidation.

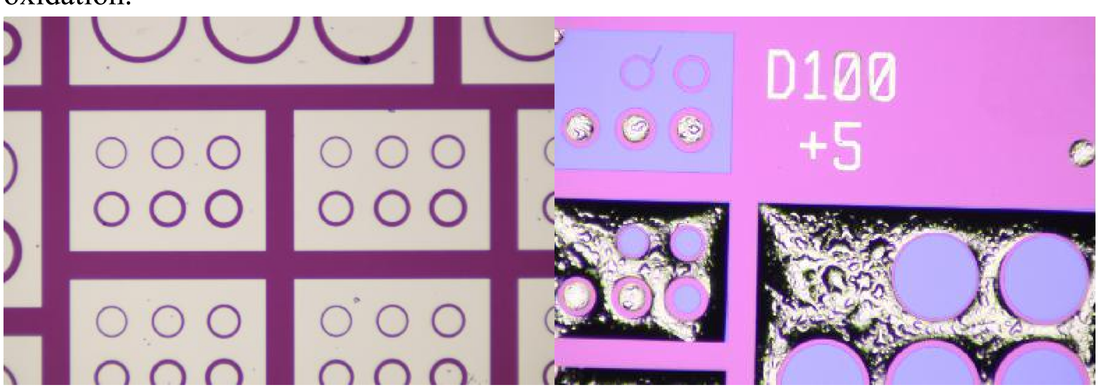

Fig 2, 3: Shows the result of a usable sample on the left compared to an unusable sample on the right.

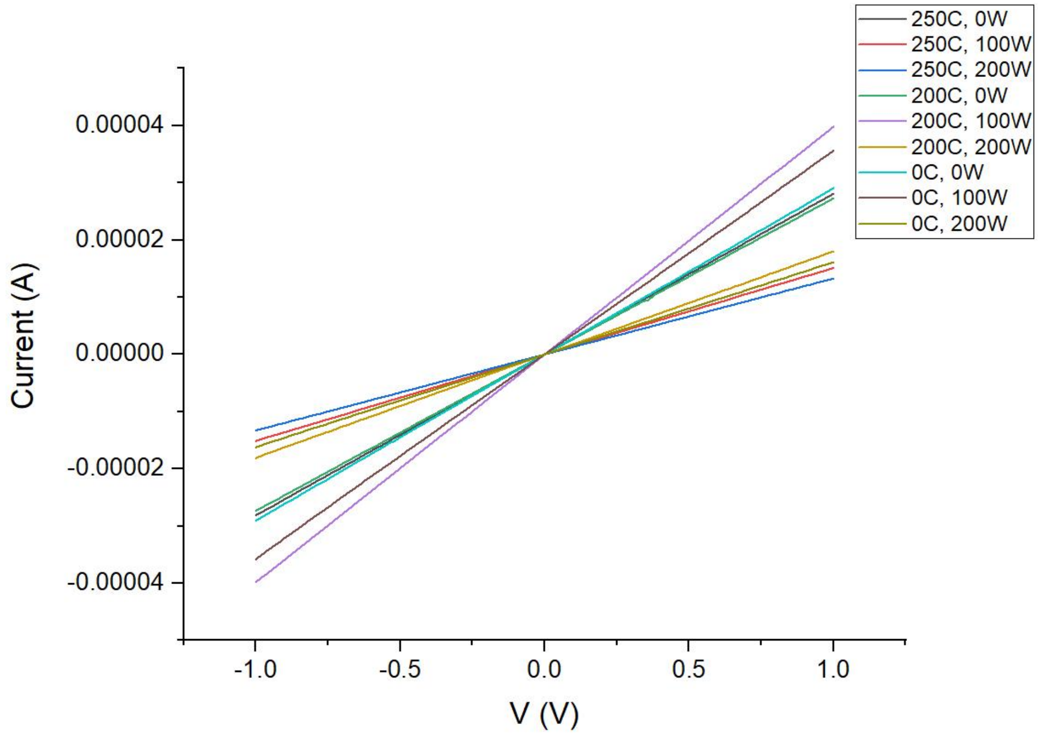

Fig 4: Graph comparing all I-V curves of the largest CTLM circle, all exhibiting Ohmic properties.

Annealed Temperature	O2 Plasma	Rsh(Ω/sq)	Rc (Ω · cm)	ρc (Ω · cm2)
x	0W	67.14898711	38.84262852	0.01679
x	100W	64.05669239	29.64020489	0.01601
x	200W	131.2152794	69.98717848	0.03280
200°C	0W	47.54530005	43.76014633	0.01189
200°C	100W	44.59568479	29.46724894	0.01115
200°C	200W	136.8463651	63.64527968	0.03421
250°C	0W	45.87697576	43.79124821	0.01147
250°C	100W	136.1306895	73.61296972	0.03403
250°C	200W	145.7690398	84.69713225	0.03644

Fig 4: Table comparing the different sheet resistances under different conditions.

5. Conclusion

Carefully optimized annealing and plasma treatment significantly improve NiO contact performance. The best results suggest that NiO can serve as a viable p-type layer for Ga_2O_3 heterojunction devices. Future work will include Hall effect measurements to extract mobility and carrier concentration, guiding further device development.

6. Review and Reflection

This research provided invaluable exposure to the semiconductor industry, particularly in cleanroom operations, standard fabrication processes, and the broader research and development cycle. I gained firsthand experience working with advanced materials such as Gallium Nitride and Gallium Oxide, deepening my understanding of their roles in next-generation electronics. I am especially grateful to Professor Wong King-Yuen for sharing his passion for the field and for guiding me through every stage of the research journey—from literature review and experimental design to hands-on execution. I also sincerely thank the senior lab members for their patience and mentorship throughout this project.