Role of Dopant Engineering in Thermal Management of AlN UWBG Electronics

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Introduction

Aluminum Nitride (AlN) is an ultra-wide bandgap (UWBG) material with exceptional intrinsic properties, including a bandgap of 6.1 eV, high room temperature thermal conductivity (~317 W/mK), and a large breakdown field strength, and Johnson figure of merit [1]. Recent breakthroughs achieving both n-type (Si) and p-type (Be) doping have unlocked the possibility of bipolar AlN electronics with high power densities [2], [3]. However, the process of doping introduces impurities and defects that can strongly scatter phonons and degrade thermal transport. Because self-heating and the dissipation of thermal energy are critical for high power devices, the impact of dopants and the doping process on the thermal properties of AlN must be understood to properly design AlN electronics [4]. To improve our understanding of the transport properties of doped AlN, this study investigates the thermal conductivity and thermal boundary resistance between metals and doped AlN thin films with an emphasis on correlating thermal transport with the lattice damage, doping concentration, growth methods, and post-annealing treatments.

Experimental Procedures

N-type (Si) and P-type (Be) AlN films were grown by MOCVD using in situ pulsed doping (Si) and ex situ ion-implantation (Be, Si). Post-implantation, samples were annealed to recover crystallinity. Thermal conductivity was measured using time-domain and steady-state thermoreflectance (TDTR, SSTR). Samples were analyzed using high-resolution TEM combined with EDX to probe ion distribution, implantation-induced damage, and defect formation. These structural results were correlated with TDTR measurements to identify different sources of phonon scattering in doped AlN.

Results and Discussion

Thermal conductivity measurements highlight the strong sensitivity of AlN to doping-induced lattice disorder (Fig. 1). For n-type Si-implanted films (~200-300nm), conductivity dropped by nearly an order of magnitude (17-23 W/mK) but partially recovered after annealing (122-129 W/mK), with CW growth yielding slightly higher values than pulsed MOCVD. For p-type Be-doped AlN (~2um), conductivity was similarly reduced in the as-implanted state (23 W/mK) but was nearly restored to bulk-like levels after annealing (~223 W/mK). While the data suggests distinct recovery behaviors between Si- and Be-doped films, these differences may also reflect extrinsic factors such as thickness, variations in dopant concentration and distribution. Nevertheless, the overall trends consistently demonstrate that ion-implantation introduces substantial lattice disorder, and post-annealing is essential to recover thermal transport. These results show that doping-induced phonon scattering is a key limitation to preserving AlN's intrinsic conductivity and highlight the need for combined structural and compositional analysis to fully disentangle the role of dopant species from processing effects.

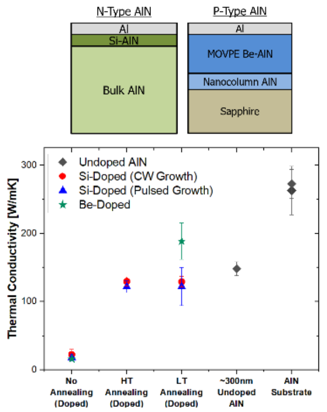

Figure 1: Thermal conductivity of doped AlN films post-implantation

References

[1] Z. Cheng *et al.*, "Experimental observation of high intrinsic thermal conductivity of AlN," *Phys Rev Mater*, vol. 4, no. 4, Apr. 2020, doi: 10.1103/PhysRevMaterials.4.044602.

[2] M. L. Nakarmi, K. H. Kim, K. Zhu, J. Y. Lin, and H. X. Jiang, "Transport properties of highly conductive n-type Al-rich Al xGa 1-xN (x≥0.7)," *Appl Phys Lett*, vol. 85, no. 17, pp. 3769–3771, Oct. 2004, doi: 10.1063/1.1809272.

[3] H. Ahmad, J. Lindemuth, Z. Engel, C. M. Matthews, T. M. McCrone, and W. A. Doolittle, "Substantial P-Type Conductivity of AlN Achieved via Beryllium Doping," *Advanced Materials*, vol. 33, no. 42, Oct. 2021, doi: 10.1002/adma.202104497.

[4] G. Li, Z. Cui, and R. Guo, "Impact of point defect charge states on the thermal conductivity of AlN," *Phys Rev B*, vol. 111, no. 9, Mar. 2025, doi: 10.1103/PhysRevB.111.094102.