Proceedings of CONF-APMM 2026 Symposium: Quantum Communication and Model Simulation
DOI: 10.54254/2753-8818/2026.GL35835

Multifunctional Aluminum Nitride P-N Diodes Spanning High Voltage and RF Front-End Applications

Chenxi Shi

School of Management, Technical University of Munich, Munich, Germany
go39diw@mytum.de

Abstract. Aluminum nitride (AlN) is distinguished by three outstanding physical properties: an ultra-wide bandgap, a high critical breakdown electric field, and a substantial piezoelectric effect, making it suitable for extreme-environment electronics and radio frequency (RF) systems. This review focuses on AlN-based p-n junction diodes, with emphasis on their application prospects in high-voltage power switching devices and RF front-end integration. After reworking the theoretical underpinnings, the paper analyzes the polarization-induced deviation of AlN from standard p-n junction models and the resulting impact on tunneling-assisted carrier transport. At the application level, three directions are then addressed: high-voltage PIN switches for power grid regulation, solar-blind ultraviolet (UV) photodetectors for assessing AlN's optoelectronic performance, and bulk acoustic wave (BAW) resonators with monolithic integration into RF front-end circuits. Fabrication challenges are also considered, particularly ohmic contact formation and surface passivation stability, which emerge as the principal bottlenecks. These bottlenecks pave the way for constructing a strategic roadmap, which provides theoretical perspectives for exploiting AlN's Multiphysics coupling and enables next-generation fully integrated intelligent power and RF microsystems.

Keywords: Aluminum Nitride, p-n junction diodes, Wide-bandgap semiconductors, RF-Photonics, Acoustic-optics

1. Introduction

Wide-bandgap semiconductors have consistently attracted research attention over recent years, with Takashi et al. attributing their versatility to three fundamental features [1]. The strong lattice bonding and high chemical-bond energies keep outer electrons tightly bound, resulting in exceptional mechanical hardness and a high Debye temperature. These properties enable deployment in aerospace and nuclear sectors, as well as stable operation under extreme temperatures and intense radiation. The wavelength of emitted or absorbed light is directly set by the bandgap width and direct-bandgap semiconductors (e.g., GaN, ZnO, ZnSe). They are critically important for realizing high-efficiency light emission because they support radiative recombination processes with very little phonon participation. After the blue LED was introduced, the three primary colors gradually replaced the conventional energy-intensive lighting approaches, thus bringing about solid-state white lighting. At the same time, UV lasers, which operate at shorter wavelengths,

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directly accelerated the advancement of high-density DVD storage technology. These lasers play an irreplaceable role in solar-blind UV detection, because they function entirely outside the visible spectrum. As noted in reference [2], even traditional III-V semiconductors suffer a marked drop in luminous efficiency under high-density dislocation defect conditions, whereas GaN-based blue LEDs maintain remarkably high emission efficiency. This property is rooted in the large effective mass of charge carriers and the consequently short minority carrier diffusion length characteristic of wide-bandgap semiconductors.

Conventional semiconductors (Si) and wide-bandgap semiconductors (SiC) are seemingly mature in integrated circuits, but there are still some downsides that need to be conquered. Silicon-based conventional materials, constrained by intrinsic material characteristics, encounter pronounced limitations under high voltage, high operating temperatures, and high switching frequencies. While SiC has managed to address some of the mentioned difficulties, notable bottlenecks persist with respect to manufacturing processes, device design, and long-term operating stability. The dynamic on-resistance fluctuations of SiC during operation may even trigger catastrophic thermal runaway under specific system conditions. Such extreme local power densities and associated thermal-management challenges point to SiC power devices as, at this juncture, still constituting the principal limiting factor for their full-lifecycle reliability.

Within the realm of frontier applications that target RF-photonic monolithic integration, AlN p-n junction diodes act as a crucial foundational element for surmounting frequency-band limitations and achieving high-efficiency optoelectronic coordination. A thorough investigation into the fundamental operating principles of these p-n junctions and the intrinsic crystalline structure of AlN is carried out, with the purpose of laying a solid theoretical groundwork for the next generation of highly integrated high-voltage and RF front-end microsystems. This investigation starts from a theoretical framework rooted in the material's core polarization effect, and then broadens to encompass a systematic review of switching devices, photodetection, and RF applications.

2. Theoretical fundamentals

AlN hardly fits the mold of an ordinary semiconductor; rather, it stands as one of the most defining enablers across the family of ultra-wide-bandgap materials, which can be comprehensively reviewed by Yu’s research [3]. Compared with first-generation silicon, which offers only a 1.12 eV bandgap, AlN possesses an intrinsically ultra-wide gap of 6.2 eV. The figure exceeds the corresponding values for SiC and GaN. The wide gap strongly suppresses the undesired thermal excitation of charge carriers, keeping the intrinsic carrier concentration at a low level even when the temperature is extreme. It is what clearly distinguishes AlN from many other semiconductors, endowing it with high-frequency and high-power-density applications. Moreover, AlN is also known as an extreme semiconductor. Take the critical breakdown electric field: it reaches 12 MV/cm in AlN, more than four times the value found in GaN. This characteristic alone makes AlN a strong candidate for ultra-high-voltage power grid infrastructures. AlN also benefits from a thermal conductivity, because it is higher than that of most materials, thus affording both outstanding resistance to high temperatures and rapid dissipation of heat. In addition, the solar-blind nature of AlN is particularly advantageous for deep-ultraviolet photodetector chips, since it makes those devices inherently immune to solar background radiation.

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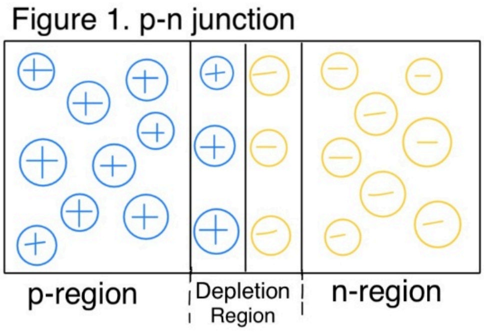

Figure 1. P-N junction

As shown in Figure 1, a conventional abrupt p-n junction is schematically illustrated. However, this classical depiction serves merely as a reference; it does not apply to AlN. The structural model defines such a p-n junction by a step-like change. This occurs precisely at the metallurgical interface that separates the uniformly doped p-region from the n-region. Owing to the steep concentration gradient across that metallurgical boundary, the majority carriers begin to diffuse into the opposite region; at thermal equilibrium, only immobile, positively charged donor atoms and negatively charged acceptor atoms remain on their respective sides of the interface. This region is the so-called space charge region or depletion region. However, the classical homojunction electrostatics theory summarized by Bernardo et al. encounters severe physical limitations when applied to ultra-wide bandgap semiconductors, such as AlN [4]. Due to the great bandgap, the intrinsic carrier concentration is practically zero. This will lead to a built-in potential significantly higher than that of GaN or SiC, generating an extremely wide intrinsic potential barrier. Given the extremely high activation energy of acceptor impurities (e.g., Mg) in AlN (above ~0.5 eV), which results in negligible hole concentration at room temperature and renders conventional diffusion doping ineffective, polarization-induced doping or tunnel junction must be applied to bypass the limits of conventional p-n junctions.

For both conventional narrow-bandgap and wide-bandgap semiconductors, the standard depletion-layer model provides an accurate description of zero-bias equilibrium states, forward-bias minority carrier injection, and reverse-bias blocking characteristics [5, 6]. Nevertheless, a direct extension of this theoretical framework to AlN reveals two critical deviations. First, the electrostatic deviation: the pronounced spontaneous and piezoelectric polarization effects inherent to AlN induce fixed sheet charges at the junction interface. Under an applied bias, this charge nonlinearly alters the variation laws of the built-in potential and the depletion layer width, an effect that is entirely overlooked by the classical model. Second, the transport regime deviation: the intrinsic carrier concentration of AlN drops to a negligible level of approximately 10^{-34} cm^{-3} to 10^{-31} cm^{-3}at room temperature, invalidating the conventional diffusion-recombination physical picture. Consequently, the injection of minority carriers becomes practically negligible; instead, carrier transport within AlN p-n diodes transitions into a regime where either trap-assisted tunneling or polarization-induced band-to-band tunneling dominates the conduction mechanism. Meeting the demands of next-generation RF-Photonics monolithic integration, therefore, requires device designs that explicitly account for non-equilibrium carrier dynamics, for instance, through polarization-induced doping and heterojunction tunnel contacts—since these approaches are indispensable for surmounting the intrinsic physical barrier outlined earlier.

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3. Applications

3.1. P-N junction switch

The switching behavior of a p-n junction forms the basis for digital logic and power control in semiconductor devices such as diodes and transistors. Its underlying mechanism relies on reversing the polarity of the externally applied voltage, thereby toggling the junction between a high-conduction state (on) and a high-impedance blocking state (off). Under forward bias, the external electric field opposes and reduces the internal built-in field, so that the majority carriers diffuse into the opposite regions and generate a strong current. The junction is placed in a low-resistance (on) condition. Under reverse bias, the external field widens the depletion region, suppressing the diffusion of majority carriers. Only a minute drift of minority carriers remains, producing a saturation leakage current. And the junction then enters a high-impedance (off) state. When dynamic switching characteristics are taken into account, the situation changes. During forward conduction, a large number of non-equilibrium minority carriers are stored in the base region, which manifests as the minority-carrier storage effect. Upon a sudden reversal of the applied voltage, those stored carriers must be gradually removed through reverse extraction and recombination. This process generates a substantial reverse recovery current in the external circuit, causing heavy switching losses that restrict the operating frequency.

For ultra-high-voltage (kV-class) applications in high-power smart grids and high-frequency radio-frequency power switching, AlN has drawn considerable attention owing to its ultra-wide bandgap (~6.2 eV) and extremely high theoretical breakdown electric field (>12 MV/cm). The practical use of AlN-based PIN switches in high-voltage power control faces serious obstacles, mainly the high ionization activation energies and interfacial contact resistances. This is associated with conventional chemical dopants (e.g., Mg and Si). To get around this critical limitation, researchers have recently turned to polarization-induced doping as an alternative. Faber et al. performed two-dimensional electrical simulations [7]. Their findings indicate that proper polarization-induced band engineering can generate a high density of effective charge at interfaces without recourse to chemical doping. This approach reduces the forward ohmic contact resistance and optimizes the conduction characteristics. This theoretical framework opens up a novel route for constructing low-loss conduction layers in high-voltage AlN PIN switches. On the experimental front, AlN diodes have demonstrated electric field endurance approaching the physical limits in high-voltage. Ahmad et al. fabricated a quasi-vertical p-AlN/i-GaN/n-GaN heterojunction PIN diode on a heteroepitaxial wafer [8]. Although the achieved breakdown field (~1.25 MV/cm) remains substantially below the theoretical limit of AlN (12 MV/cm) because of heteroepitaxial defects, this work successfully validates the formation of low-resistance ohmic contacts and the occurrence of conductivity modulation in the AlN-based PIN structure.

3.2. P-N junction solar-blind photodetector

Beyond power switching, AlN can also be used in solar-blind detectors because of its ultra-wide bandgap. This application is crucial for monitoring the arc flash in high-voltage power grids. When solar-blind ultraviolet light with a photon energy exceeding the bandgap strikes the depletion region, the material absorbs the photons and generates electron-hole pairs. Under the huge influence of the built-in electric field inside the p-n junction, the newly generated electrons and holes are rapidly separated and drift in opposite directions, thus yielding a photocurrent through the external circuit.

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In core solar-blind ultraviolet (UV) detection applications such as missile approach warning, deep-space exploration, and unattended field environmental monitoring, devices are often required to exhibit an extremely high signal-to-noise ratio and exceptionally fast photo response under zero-bias or low-bias operating conditions. Despite the promise of AlN/AlGaN for advanced device applications, conventional structures with high Al content are seriously limited by interfacial defects and alloy scattering. These issues give rise to relatively large dark currents, and at the same time, the collection and transport of photogenerated carriers are constrained by inherent physical bottlenecks. To overcome these difficulties, Fang et al. proposed in 2024 an interfacial spacer-layer engineering strategy, in which a nanoscale, ultrathin AlN spacer is inserted precisely between the high-Al-content barrier layer and the low-Al-content channel of an AlGaN heterostructure [9]. This approach takes advantage of the strong discontinuity in both spontaneous and piezoelectric polarization, thereby producing an increase in the effective conduction-band offset. The enhancement not only improves the spatial separation of photogenerated electron-hole pairs but also raises the off-state potential barrier for electrons. Consequently, the photo-to-dark current ratio (PDCR) of the device is improved by roughly an order of magnitude.

With the further pursuit of enhanced polarization-field-induced charge density at heterointerfaces, device architectures have also evolved from conventional diode structures toward phototransistors capable of high internal amplification gain. In 2025, Peng et al. further advanced this field by proposing a more innovative binary AlN/GaN interfacial layer engineering technique [10]. The researchers embedded an ultrathin binary double-spacer layer within an $Al_{0.61}GaN/Al_{0.53}GaN$ heterostructure, and through precise manipulation of the local polarization-charge tensor and carrier confinement effects at the heterointerface. Without introducing external chemical dopants, a 25-fold increase in the sheet density of the polarization-induced two-dimensional electron gas (2DEG) was achieved. Simultaneously, electron mobility was enhanced by 36% owing to the effective mitigation of the severe alloy scattering inherent to high-Al-content material lattices.

3.3. RF switches based on PIN diodes

Between the conventional p-type and n-type semiconductors, a high-resistivity intrinsic layer, known as the i-region, is inserted. While the rectifying characteristics of a PIN diode remain valid under low-frequency or DC conditions, its high-frequency behavior is fundamentally governed by the carrier dynamics. In the RF band, the period of the alternating signal is much shorter than the minority carrier lifetime in the i-region. Consequently, the PIN diode cannot respond to individual RF cycles; instead, its impedances lack the time to alternate between the positive and negative half-cycles, causing it to behave as a linear impedance controlled by the DC bias rather than actively rectifying the high -frequency signal. For RF switches, this allows the device to bypass cycle-by-cycle rectification and function as a current-controlled variable resistor. By introducing an ultra-low resistance under forward bias and a tiny junction capacitance under reverse bias into series or shunt RF networks, one can perfectly achieve low-loss transmission or high-isolation blocking of RF power.

Modern 5G/6G radio-frequency front-end (RFFE) systems demand two core functionalities: band switching and isolation via PIN switches, and precise filtering using high Q-factor resonators. Traditional RFFE architectures commonly use GaAs- or Si-based materials for PIN switches, whereas high-performance bulk acoustic wave (BAW) resonators depend on piezoelectric materials such as AlN. AlN offers a strong piezoelectric effect that makes it suitable for BAW resonators. Owing to its ultra-high breakdown electric field and low dielectric constant, AlN is an ideal semiconductor for high-frequency, high-power PIN switches fabrication. In 2015, Zou proposed an

AlN Lamb-wave resonator design tailored for RF front-end applications [11]. This design incorporated a silicon dioxide temperature-compensation layer and an improved butterfly-shaped plate structure. They together significantly improved the resonator's frequency stability and Q-factor while reducing its characteristic impedance. As a result, low insertion loss, compact monolithic integration, and excellent thermal stability of RF front-end filters and oscillators were satisfactorily met. More recently, Li et al. introduced a hybrid design strategy for ultra-high-frequency module integration [12]. Their strategy combined a novel Al (Sc)N-based BAW resonator with integrated electromagnetic circuit elements and employed a periodic inversion fabrication process. This approach resolved the low electromechanical coupling coefficient of pure-AlN at high frequencies and improved RF front-end power handling for large-bandwidth and ultra-high-frequency use.

4. Challenge and outlook

The surge in data traffic and the growing complexity of RF front-end designs have rendered conventional single-function chips insufficient for today's computing demands. Consequently, the next-generation hardware design lies in monolithic integration, combining high-voltage power switching with RF front-end functions on a single substrate. AlN emerges as a prime material for this integration, offering both an ultra-wide bandgap and strong piezoelectricity. Yet the wide-bandgap severely impairs ohmic contact resistance, creating a major hurdle for practical devices. At the metal interface, the barrier height is so large that electrons cannot cross it. The junction, therefore, exhibits pronounced rectifying behavior instead of the desired ohmic contact. Beyond this intrinsic barrier, AlN also suffers from surface instability under normal operating temperatures: it readily reacts with ambient oxygen, forming a native oxide layer several nanometers thick, accompanied by a high density of point defects. Moreover, the conflicting material requirements for high-voltage power components and RF units make seamless integration and commercialization challenging. From a system-level viewpoint, the inherent trade-off between power-handling capability and RF signal integrity has become even more acute. The integration process itself introduces a fundamental fabrication conflict: a thick drift layer is essential for voltage endurance, whereas high-frequency BAW resonators demand high-quality piezoelectric thin films. These two functional blocks impose divergent conditions on epitaxial growth, doping profiles, and thermal budgets, effectively precluding simultaneous fabrication.

Given the strong momentum towards monolithic integration of high-voltage and RF functions, AlN's role extends beyond traditional power switching. It offers a material platform for jointly optimizing voltage-blocking capability and RF performance. However, a basic design conflict over performance trade-offs remains embedded in the scheme. On the one hand, power devices need thick, lightly doped drift layers to maximize breakdown voltages. On the other hand, RF BAW resonators require precise film thickness control and extremely low defect densities to achieve high Q-factors and low insertion losses. To resolve this dilemma, future work will concentrate on selective-area doping through graded AlScN heterojunctions, enabling spatially tailored device performance on a single chip. Following this technological direction, the monolithic integration of AlN-based high-voltage PIN switches with RF front ends could become a transformative breakthrough, with the potential to reshape next-generation 6G transceivers and smart grid modules.

5. Conclusion

This work begins with an in-depth look at wide-bandgap AlN semiconductors and the theory of their p-n junctions, while stressing the inadequacy of classical junction models for AlN and the essential contribution of polarization-induced doping. From that theoretical basis, the discussion proceeds to a systematic grouping of AlN-based power and RF devices, providing a broad overview of recent research results aimed at high-voltage power switching and RF front-end uses. A range of experimental and computational studies now indicate that this material system has achieved a level of technological maturity that allows a variety of high-performance devices to be realized on a single AlN wafer. On the basis of a detailed device classification, the analysis lays out the internal connections and fabrication hurdles for high-voltage and RF monolithic integration, with particular attention to the severe trade-off between thick drift layers needed for voltage blocking and the piezoelectric films essential for BAW operation. The paper closes by offering a solid theoretical foundation and a coherent set of design guidelines for future fully monolithic high-voltage/RF integrated circuits. Looking ahead, ongoing efforts in AlN research are expected to concentrate on optimizing power-RF co-integration, with the prospect of realizing monolithic combinations of high-efficiency power switches and high-performance RF filters on a single high-resistivity insulating AlN substrate wafer.

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