Semiconducting AlN: A New Rapidly Emerging III-Nitride Market

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Abstract

Aluminum nitride (AlN) is a material of great interest for near future applications including high performance power electronics, extreme environment semiconductor devices, radio frequency (RF) devices, and deep ultraviolet (DUV) optoelectronics due to its excellent electrical, optical and thermal properties [1-3]. Compared to other commonly used semiconductors (i.e., Si, SiC, GaN, and β-Ga_2O_3), AlN has the highest critical electric field and theoretical breakdown voltage, which leads it to have the highest Baliga's and Johnson's figures-of-merit [3]. AlN also has one of the highest saturation velocities and thermal conductivities among the semiconductors with a commercially available substrate [3]. However, AlN has traditionally only been an insulator without the ability to be converted to a semiconductor via substantial doping. We recently demonstrated substantial bulk doping (carrier concentrations above 10^{18} cm^{-3}) for both p- and n-type AlN using Be and Si dopants, respectively [1,2]. From these results, we also demonstrated rectification and a 6 V turn-on in AlN PN diodes [2,3]. Early transistor structures show over 350 mA/mm current density at V_{DS}=10V for n-channel devices and ~30 mA/mm at V_{DS}=30V for p-channel devices with significantly more improvement expected quickly. Given the existing infrastructure to support AlN devices and the leap in performance possible with a 6.1 eV bandgap material with high thermal conductivity, it is anticipated that AlN markets will develop rapidly with many devices developing in parallel, lowering overall ecosystem costs and delivering the highest performance semiconductor platform to date.

INTRODUCTION

Why develop another semiconductor ecosystem? As described in Table 1, AlN has the largest bandgap of any semiconductor with a commercially available substrate, nearly double that of GaN and SiC, the two most successful wide bandgap semiconductors available today. This much larger bandgap affords massive jumps in performance with AlN having both the highest critical field and Baliga's and Johnson's figures-of-merit. AlN is the only semiconductor solution known presently for deep UV optics (~200 nm wavelength LEDs, LASERs, and photodetectors). In RF and power switching electronics, AlN offers far more than just an evolutionary improvement in device performance compared to mature GaN and SiC wide bandgap semiconductors that are the dominant players in RF and power electronics. Additionally, AlN shares ecosystem infrastructure (substrates, epitaxy tools, fabrication tools, supply chain, etc.) with its little brother, GaN, making the cost of development a small fraction of what is normally required to take a semiconductor from infancy to maturity. Yet, unlike GaN, a robust physical vapor transport (PVT) AlN substrate technology exists (2" is common, with 4" demonstrated but not yet for sale) with a known cost and time model borrowed from SiC PVT experience, suggesting 6-8" wafers could be available by 2030 if demand warrants further investment. Finally, AlN is here today, with development requiring only engineering time, not significant technological breakthroughs.

EMERGING MARKETS

Three obvious and near-term markets exist for AlN: Optoelectronics (particularly emitters); Switching power electronics; and RF electronics.

Optoelectronics

In recent years, DUV LEDs have targeted ~270 nm because this wavelength is readily absorbed by viral and bacterial organics. This wavelength is at "a" peak of the "extinction curve" describing the strength of absorption and the tendency to disrupt the replication of viral/bacterial species. However, an even more sensitive peak exists in the extinction curve around 200 nm indicating a more efficient means of sterilizing against viral and bacterial species that aligns well with the AlN emission peak. For this reason, AlN DUV LEDs are of great interest and have yet to be demonstrated. The development of strong DUV light sources would enable optical sterilization of virtually any surface without concern for interaction with humans. 200 nm light is safer than 270 nm light in that it is absorbed in dead layers of the skin and is less prone to cause skin cancer.

Switching Power Electronics

In many electronic applications, AlN stands alone in its ability to switch very high voltage devices owing to the practical reality that lesser capable semiconductors need unrealistic device thicknesses not easily achieved with current epitaxial

Material	**E_G (eV)**	**$V_{Saturation}$ (10^7 cm/s)**	**$E_{Critical}$ @ 10^{16} cm^{-3} (MV)**	**Thermal Conductivity (W/m-K)**	**Johnson FOM (10^{12} V/S)**	**Available Substrate?**	**N-type?**	**P-type?**	**Light Emission ?**
Si	1.12	1.0	0.3	145	0.48	Yes	Yes	Yes	No
SiC	3.26	2.0	3.1	490	10	Yes	Yes	Yes	No
GaN	3.45	1.4	4.9	253	11	Almost	Yes	Yes	Yes
β-Ga_2O_3	4.8	1.1	10.3	27	18	Yes	Yes	No	No
AlN (Parameter Rank)	6.1 (#1)	1.3 (#3)	15.4 (#1)	319 (#2)	32 (#1)	Yes	Yes This Work!	Yes This Work!	Yes

technologies [3]. Conversely, AlN requires ~0.7 μm/kV, making devices of many 10's of kV practical with present-day epitaxial tools. Given the conservative adoption stature for the commercial power electronics market, the Department of Defense would be a more likely candidate for early commercial adoption. High voltage DC-DC, AC-DC, and DC-AC converters are critical to future electronic systems including the Power Electronic Building Block (PEBB) modular systems that seek ever-increasing voltage bus operation. For AlN, a 20 kV PEBB would theoretically require ~ 14 μm of epitaxy compared to >70 μm for current SiC technology, greatly lowering the cost and device design constraints. Moreover, the increased frequency of conversion enabled by AlN would lower system size by making associated reactive components smaller and easier to handle in the modular systems targeted for PEBB. Many kV solid state transformers could also be enabled or simplified (single device switches instead of series-connected switches) by AlN. These are just some of many power applications that can be enabled by having a higher voltage capable semiconductor that enables higher voltage and thus, lower conduction losses to enable never-before practical, single device switching capability.

RF Electronics

AlN is very close in performance to GaN and exceeds GaN in thermal and voltage capability and p-type conduction. With a saturation velocity 93% of GaN's and already realized electron mobilities exceeding 400 cm^2/V-sec [3], AlN gives up very little in the way of current flow to GaN's proven capability. Yet, power density in AlN RF electronics can be higher owing to a 26% higher thermal conductivity that can efficiently spread the heat away from small RF devices. Likewise, because AlN can handle 50% higher voltages for a given device length, substantial power efficiency can be achieved in AlN compared to GaN. By reducing heat generation via emphasis on voltage instead of current and with improved thermal conductivity, >50 W/mm AlN RF devices are predicted – a staggering capability.

Keys to Doping Success: Controlling Defect Chemistry with Low Temperature Synthesis

Thus, AlN is a rapidly emerging semiconductor that can offer dramatic and short-term exploitation in power switching, high temperature electronics, RF electronics and optoelectronics facilitated by breakthroughs in doping technologies enabled by low temperature, non-equilibrium epitaxy. However, AlN, like all wide bandgap semiconductors, has defect formation energies that are dependent on the Fermi-level position which is controlled by impurities and defects, not by growth temperature as found for materials such as GaAs and Si. Thus, defects and impurities typically result in self-compensation that make doping to achieve conductivity troublesome. We have found that defect and impurity compensation can be reduced by controlling the surface chemistry during growth with lower compensating vacancy concentrations being a key driver for using lower temperature growth. Contrary to common understanding, low-temperature, metal-rich vacuum processes are shown to have higher diffusion lengths than high temperature, nitrogen-rich methods [3]. This feature can be utilized to inhibit silicon-DX center formation without compromises in crystal quality.

Moreso, low temperatures lead to an exponentially lower vacancy concentration. Thus, for p-type doping where N-vacancies act as compensating donors, low temperature growth is vital for achieving p-type conductivity. Complementary arguments exist for reducing compensating Al vacancies when n-type doping AlN with Si donors. First principles calculations identify the AlN valence split-off band as the dominant hole band, and because of its anomalous position above the heavy and light hole bands, an impurity band forms at dopant concentrations lower than in GaN even with a deeper isolated acceptor energy meaning the well-proven impurity band doping in GaN can be applied to AlN over a wider range of impurity concentrations. This anomalous band structure facilitates hole mobilities that are substantially higher than possible with GaN. P-type AlN with hole concentrations of ~4.4 × 10^{18} cm^{-3} and 0.045 Ω-cm resistivity and n-type AlN with electron concentrations of ~6 × 10^{18} cm^{-3} and ~0.02 Ω-cm resistivity have been achieved. Additionally, the ability to create an impurity band expanded from the isolated acceptor and donor states has resulted in estimates of the effective activation energy of acceptors and donors being ~37 meV and ~35-50 meV, respectively [3-4], offering substantial promise for future generations of AlN unipolar electronic, bipolar electronic and optical devices.

P-TYPE PROMISE

For the same hole concentration (~4x10^{18} cm^{-3}), the hole mobility in AlN is ~10x that of GaN. This suggests promise for bipolar optics and complementary electronic technologies such as push-pull stages or digital logic not practical in GaN. Early transistor structures show over 350 mA/mm channel current density at V_{DS}=10V for n-channel devices and ~30 mA/mm at V_{DS}=30V for p-channel devices with significantly more improvement expected. This means that complementary pair layout geometry asymmetry is only about 10:1 for p:n-type AlN transistors compared to ~100:1 for GaN transistors. While still large compared to Si technology, a 10:1 layout asymmetry is manageable, enabling complementary devices while maintaining reasonable packing density.

Why is p-type AlN Better than p-type GaN?

AlN has an unusual band structure that works in its favor for p-type conduction. Specifically, in AlN, the split-off valence band is located above the heavy and light hole degenerate bands making it the primary band to interact with the deeper acceptors (like Be used in references 1-3). This means that the split-off band is the transport band for holes formed via impurity band formation [3]. Since this split-off band has stronger curvature than the heavy and light hole bands, the hole effective mass is smaller, making the hole mobility higher in this split-off band [3]. Additionally, the smaller effective mass results in ~ 10x lower dopant concentration wherein the impurity band begins to form compared to GaN. This means the benefit of the impurity band formation (increased activation efficiency, higher hole concentrations) occurs at lower doping in AlN compared to GaN.

The n-type Improvement

While prior MOCVD efforts [5-6], maxed out with an ~10^{15} cm^{-3} electron concentration at room temperature, by using the low temperature synthesis method described elsewhere [2-3], electron concentrations as high as 6x10^{18} cm^{-3} have been achieved. These non-equilibrium low temperature methods are complemented in literature by promising ion implantation work where high electron concentrations are also realized. The commonality of both methods is the avoidance of high temperatures that can result in significant vacancy generation that compensates donor doping and aggravates the tendency of Si to break its c-axis bond with N [2-3]. While higher doping concentrations may still be possible, the presently demonstrated doping values are high enough to form good ohmic contacts to as-grown (but not plasma-etched) material.

REMAINING ENGINEERING CHALLENGES

The primary challenges for AlN are engineering based, not fundamental science based. This means that with enough time and resources, all challenges can be met. Chief of the remaining challenges are the need to improve doping repeatability owing to AlN's tendency to getter impurities from the vacuum environment [1-3] and the need to improve contacts to AlN [2-3]. As shown in Figure 1, based on the standard electron affinity model, the range of available metals do not align well in energy with AlN. Most semiconductors have an electron affinity of ~4 eV. Depending on which report you believe, the electron affinity of AlN, χ, is $-0.2 < \chi < 1.9$ eV. This leads to some contact oddities. For example, experimentally, high work function metals have been used for both p-type (expected) and n-type (not expected) contacts [1-3]. It is not clear the reasons this strategy works, but it may be related to the formation of strongly bent Schottky barriers regardless of metal selected, allowing tunnel contacts to form. Current Navy-supported work is investigating the cause and offering improved contact solutions.

Contacts to plasma-etched layers needed for quasi-vertical devices (etching to make contact to buried n-type layers) are substantially worse (>100 times worse) than non-etched contacts [2-3]. Post-etching cleanup of plasma damage and surface contaminants is needed and is being explored. Use of digital etching [7] and/or commonly available plasma chemistries that are not common to GaN may offer promise. While to the best of the authors' knowledge, no one is working on conductive bulk AlN substrates, this innovation would cause the optoelectronics and power switching electronics fields to rapidly expand applications and bypass the need for quasi-vertical devices and the need to make contact to etched surfaces. One solution to achieve the same vertical conduction goal without the need for conductive wafers is to employ epitaxial liftoff. However, this approach may limit overall device area and thus, may impact high current devices.

One very promising contact solution is to use compositionally graded contacts, but this still needs to be implemented in AlN. Amano et al [8], recently demonstrated both a compositionally graded n-type and p-type contact layer to high Al composition AlGaN diodes which showed remarkable specific on-resistance of 0.003 Ω-cm^2. While at first glance this appears simple to extend to AlN, the not so well appreciated fact that polarization grades do not create free carriers but merely attract free carriers from other locations complicates the implementation. Specifically, one needs a large reservoir of free electrons and holes from which

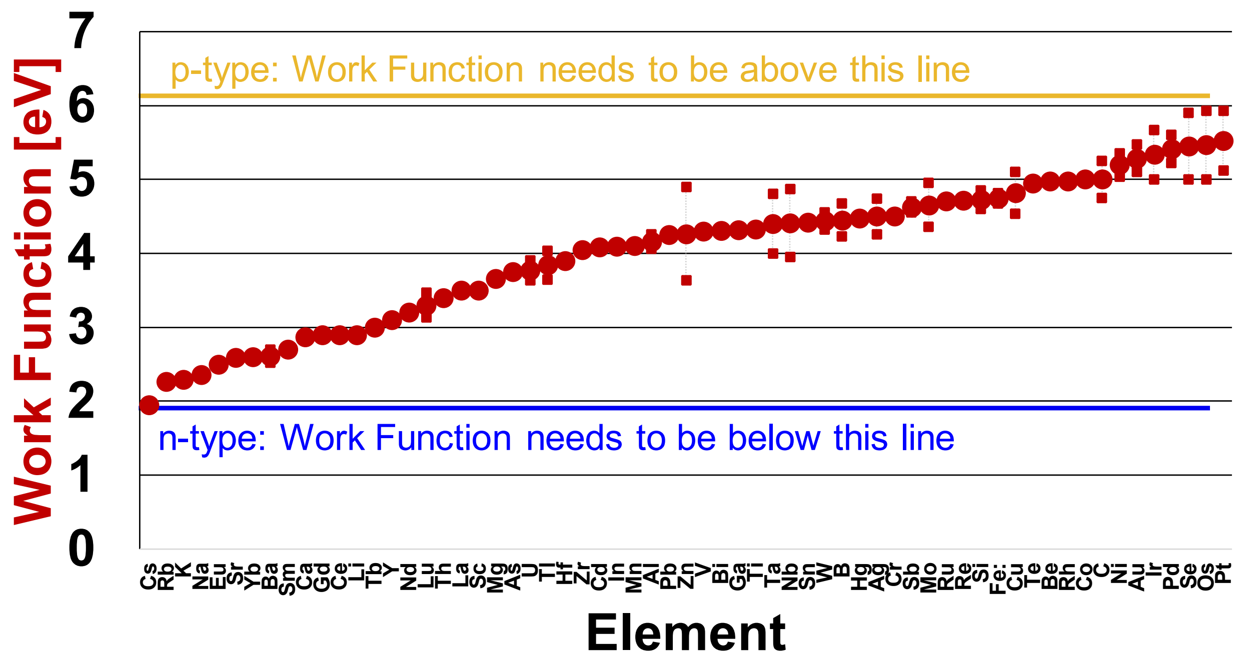

Fig. 1. Comparison of the work function of available metals to the energies needed to form ohmic contacts to n- and p-type AlN according to the electron affinity model. The electron affinity of AlN is assumed to be 1.9 eV but could be lower, making the problem more pronounced.

to draw toward the polarization graded region. Often, these carriers originate from surface states [9]. But in AlN, surface states are very well passivated by Al-oxides. Thus, it may prove more difficult to reach 100% Al compositions in graded structures. More research is needed.

CONCLUSIONS

Recent developments in semiconducting AlN, AlN that can be substantially bulk doped, has created an excitement for future electronic and optoelectronic devices with never-before realized performance. Low temperature, non-equilibrium methods have shown success in achieving semiconducting AlN with room temperature free carrier concentrations exceeding 4x10^{18} cm^{-3} for both n- and p-type conduction and has led to functional pn diodes [2-3] and early (incomplete) transistors with impressive promise. While some areas remain to be explored, contact improvement is the most immediate need and is primarily an engineering, not fundamental science, challenge. Conversely, efforts are needed to create vertical conducting devices via conductive bulk wafers or post-processing methods such as epitaxial lift off.

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ACRONYMS

AlN: Aluminum Nitride
MME: Metal Modulated Epitaxy
MBE: Molecular Beam Epitaxy
MOCVD: Metal Organic Chemical Vapor Deposition
PVT: Physical Vapor Transport