An aluminium nitride (AlN) Schottky barrier diode (SBD) was fabricated on an AlN single-crystal grown by physical vapor transport (PVT). The Ni/Au-AlN SBD features a low ideality factor $n$ of 3.3, an effective Schottky barrier height (SBH) of 1.05 eV, and an on/off ratio of $\sim 10^6$ under forward biases at room temperature. This work presents the lowest ideality factor of AlN SBDs that have been reported. As temperature increases, the effective SBH extracted from the current-voltage characteristics becomes larger while the ideality factor $n$ becomes smaller. The temperature dependences of SBH and $n$ were explained using an inhomogeneous Schottky junction model. A mean SBH of 2.105 eV was obtained by analyzing the inhomogeneity of the Ni-AlN Schottky junction. This work reveals the potential of AlN for advanced SBDs with large barrier height. An equation with parameters having explicit physical meanings in thermionic emission theory to describe the current-voltage characteristics of inhomogeneous SBDs was proposed.
Aluminium nitride (AlN), with a bandgap energy of ~6.0 eV, a thermal conductivity up to 3.2 Wcm\(^{-1}\)K\(^{-1}\) at room temperature and a high critical electric field up to 12 MV/cm, possesses a great potential in power electronics and deep UV optoelectronics.\(^1\)\(^-\)\(^3\) Though reported almost a century earlier\(^4\) than its counterpart gallium nitride (GaN)\(^5\) which has been the main force of power electronics\(^6\)\(^-\)\(^7\) and optoelectronics\(^8\), AlN based electronics are still in their infant. On one hand, the growth of high-quality AlN crystals or epilayers is still a big challenge.\(^9\)\(^-\)\(^12\) On the other hand, the much larger bandgap results in the higher activation energy of \(n/p\) dopants\(^2\) and a wider accommodation energy range for mid-gap defects or traps\(^4\)\(^,\)\(^13\). Schottky barrier diodes (SBDs) on AlN single crystal grown by physical vapor transport (PVT),\(^14\) on AlN layers homoepitaxially grown by hydride vapor phase epitaxy (HVPE),\(^15\) and on AlN epilayers grown on sapphire by metal organic chemical vapor deposition (MOCVD)\(^16\) have been reported. An AlN metal–semiconductor field-effect transistor (MESFET) on the MOCVD-grown epilayer was also demonstrated recently.\(^17\) These SBDs and MESFETs, though with their performances far from the predicted material limit, indicate the feasibility to develop AlN electronic devices.

The ideality factor \(n\) and the Schottky barrier height (SBH) are the two critical parameters to evaluate the junction quality and the potential for high-voltage blocking capability, respectively, of a SBD.\(^18\)\(^-\)\(^20\) The ideality factor \(n\), which is a unity in the ideal case, reveals the junction quality of a unipolar rectifying diode. Compared with GaN and SiC Schottky junctions, of which the ideality factor \(n\) near a unity has been achieved,\(^21\)\(^-\)\(^25\) the \(n\) of AlN Schottky junctions is still much larger. Irokawa et al.\(^14\) and Kinoshita et al.\(^15\) reported ideality factors of ~11.7 and ~8 for a Pt/AlN and a Ni/AlN Schottky junctions at room temperature, respectively. By inserting a 2-nm GaN layer, Fu et al.\(^16\) reported an ideality factor of 5.5 for a Pt/GaN/AlN Schottky junction. Due to the ultra-wide bandgap and a large value of the charge neutral level (CNL) of AlN,\(^26\)\(^,\)\(^27\) larger SBHs have always been expected for AlN SBDs. By conducting the X-ray photoelectron spectroscopy (XPS) measurements, Reddy et al.\(^28\) reported SBHs of 1.6 to 2.3 eV (2.2 to 2.4 eV) for different Schottky metals on m-plane (c-plane) AlN. However, the SBHs extracted from the current-voltage (\(J-V\)) characteristics of fabricated AlN SBDs were much smaller, ~1.0 eV.\(^14\)\(^-\)\(^16\)

In this letter, we reported a Ni/AlN SBD fabricated on a non-polar AlN single-crystal grown by PVT, with a low ideality factor \(n\) of 3.3, an effective SBH of 1.05 eV, and an on/off ratio \(~10^6\) under forward bias at room temperature. As temperature increases from 240 to 400 K, the
ideality factor \( n \) becomes smaller from 5.8 to 2.6, and the effective SBH extracted from \( J-V \) curves becomes larger from 0.8 eV to 1.3 eV. These temperature dependences indicate an inhomogeneous Schottky junction at the Ni-AlN interface.\textsuperscript{19,29-32} By analyzing the barrier inhomogeneities, a mean SBH of 2.1 eV was obtained for the Ni/AlN SBD. Capacitance-voltage (\( C-V \)) measurement was also conducted to evaluate the effective dopant density and the SBH at a flat band condition.

FIG. 1. (a) Photoluminescence (PL) spectrum of the AlN crystal excited by a 193 nm excimer laser at room temperature. (b) Surface morphology of the AlN crystal. The scanned area is 3×3 \( \mu \)m\(^2\). The RMS roughness is about 3 nm. (c) XPS spectrum of the AlN crystal.

The AlN single crystal was grown by PVT at \( \sim2200 \) °C in the \( \text{N}_2 \) atmosphere on a tungsten substrate through spontaneous crystallization. The temperature gradient was optimized to minimize surface reconstruction or decomposition during the cooling down process. An AlN single crystal with the non-polar surface was used for material characterizations and device fabrication. Figure 1(a) shows the photoluminescence (PL) spectrum of the AlN crystal excited by a 193 nm excimer laser at room temperature. The PL spectrum, which was recorded by a QE-Pro Ocean Optics spectrometer, consists of a strong bandedge emission with peak of \( \sim6.0 \) eV, a UV band and a weak red band. The strong bandedge emission also confirms that the PL emission is from a non-polar surface.\textsuperscript{2,33} The peak-height-ratio (\( R \)), between the bandedge emission and the UV emission, is approximately 3.2. This large \( R \) value indicates the high quality of the AlN crystal.\textsuperscript{34,35}

The surface morphology of the AlN crystal was examined by atomic force microscopy
(AFM). The root-mean-square (RMS) roughness of a 3×3 μm² area, as shown in Fig. 1(b), is about 3 nm. Figure 1(c) shows the X-ray photoelectron spectroscopy (XPS) of the AlN single crystal. Oxygen is the only impurity in the AlN crystal grown by PVT on a tungsten substrate. This is consistent with the peak positions of the UV band and the red band, which are commonly identified to be the emissions from ($V_{Al}$-$O_N$) complexes.\textsuperscript{34,36} The weak Ar-related peaks result from the in-situ surface cleaning by Ar plasma in the XPS chamber.

![Figure 1](image1.png)

**FIG. 1.** (a) Atomic force microscopy (AFM) image of the AlN single crystal. The root-mean-square (RMS) roughness of a 3×3 μm² area, as shown in Fig. 1(b), is about 3 nm. Figure 1(c) shows the X-ray photoelectron spectroscopy (XPS) of the AlN single crystal. Oxygen is the only impurity in the AlN crystal grown by PVT on a tungsten substrate. This is consistent with the peak positions of the UV band and the red band, which are commonly identified to be the emissions from ($V_{Al}$-$O_N$) complexes.\textsuperscript{34,36} The weak Ar-related peaks result from the in-situ surface cleaning by Ar plasma in the XPS chamber.

![Figure 2](image2.png)

**FIG. 2.** (a) Optical image of the fabricated Ni/Au-AlN Schottky barrier diode (SBD). (b) Current-voltage characteristics of the Ni/Au-AlN SBD at room temperature. The inset shows the current-voltage characteristics of the ohmic contacts, in compare with that of the Schottky contact.

The electrodes of the Ni/AlN SBD were fabricated using shadow masks. For Ohmic contacts, metal stacks of Ti/Al/Ni/Au were first deposited by e-beam evaporation and annealed at 900 °C for 30 s in the N₂ atmosphere using rapid thermal annealing (RTA). For the Schottky contact, a metal stack of Ni/Au was evaporated by e-beam evaporation and annealed at 350 °C for 5 min. The $J$-$V$ characteristics of the Ni/AlN SBD was measured in a Physical Property Measurement System (PPMS) using a HP4155A Semiconductor Parameter Analyzer.

Figure 2(a) illustrates the optical image of the fabricated Ni/AlN SBD. Figure 2(b) plots the $J$-$V$ curve of the Ni/AlN SBD measured at 300 K. Under forward biases, an on/off ratio of $\sim$10$^6$ is obtained, which is similar to the reported values.\textsuperscript{14-16} The $J$-$V$ curve of a SBD can be described by an empirical equation,\textsuperscript{18}
Here, $J$ is the current density, $A^*$ is the Richardson constant of the semiconductor, $T$ is temperature, $n$ is the empirical ideality factor, $k$ is the Boltzmann constant, $q$ is the element charge, and $q\Phi_{B,(0,T)}$ is the zero bias SBH with image-force lowering. The subscript $(0,T)$ is due to the fact that the SBH here is calculated from $J_0$ which is the intercept at zero bias of the extrapolation of the linear segment of $(\ln J)-V$ curve at temperature $T$. Taking the value of $A^* \approx 57.6$ $\text{A/cm}^2\text{K}^2$ for AlN, the ideality factor $n$ and SBH of the Ni/AlN SBD at 300 K were extracted to be 3.3 and 1.05 eV, respectively, from the linear segment of $J-V$ curve in semi logarithmic scale. Compared with previous results, the low ideality factor $n$ of 3.3 indicates the high quality of the Ni-AlN Schottky junction achieved in this work. It is worth to be pointed out that the current-voltage characteristics between the two ohmic contacts are sublinear. Higher annealing temperature or contact metal with lower work functions is required to further decrease the contact resistance. Nevertheless, as shown in the inset of Fig. 2(b), the resistance of the non-ideal ohmic contact is several orders smaller than that of the Schottky junction contact, and its effect on the extraction of the junction parameters from the linear segment of $(\ln J)-V$ curve is negligible.

![Graph](image-url)

**FIG. 3.** (a) Current-voltage curves of the Ni/AlN SBD at different temperatures. (b) Extracted ideality factor and the effective Schottky barrier height of the Ni/AlN SBD at different temperatures.

Figure 3(a) shows the $J-V$ curves of the Ni/AlN SBD at different temperatures. The fitted values of the ideality factor $n$ and the effective SBH as functions of temperature are plotted in Fig. 3(b). As temperature increases from 240 to 400 K, the ideality factor $n$ becomes lower from 5.8 to 2.6, and the effective SBH becomes larger from 0.8 to 1.3 eV. These temperature dependences indicate that the Schottky junction at Ni-AlN interface is inhomogeneous.
Assuming the local Schottky barriers at the Ni-AlN interface follow a Gaussian distribution

\[ P(\varphi_B) = \frac{1}{\sigma(0,0)\sqrt{2\pi}} \exp\left[-\frac{(\varphi_B^{mean} - \varphi_B)^2}{2\sigma(0,0)^2}\right], \quad \text{and } \int_{-\infty}^{+\infty} P(\varphi_B) d\varphi_B = 1. \quad (2) \]

Here the barrier potential fluctuation or distribution is assumed to be independent of temperature \( T \) but may be affected by the applied biases due to the existence of image-force lowering.\(^{18} \) The current density from metal to semiconductor in thermionic emission theory can be written as,

\[ I_{ms} = A^* T^2 \exp\left(-\frac{q\varphi_{B,(V,T)}^{I-V}}{kT}\right) = A^* T^2 \int_{-\infty}^{+\infty} \frac{1}{\sigma(0,0)\sqrt{2\pi}} \exp\left[-\frac{(\varphi_B^{mean} - \varphi_B)^2}{2\sigma(0,0)^2}\right] d\varphi_B, \quad (3) \]

Integrating of Eq. (3) directly results in that,

\[ \varphi_{B,(V,T)}^{I-V} = \varphi_B^{mean} - \frac{\sigma(0,0)^2}{2kT/q}, \quad (4) \]

Therefore, the junction inhomogeneity of which the potential fluctuation or distribution is temperature independent leads to the temperature dependence of the effective SBH extracted from the \( J-V \) curve of a SBD, mathematically. For an ideal homogeneous Schottky interface, the SBH becomes lower slightly at higher temperatures due to the temperature dependence of the semiconductor’s bandgap.\(^{18} \) For an inhomogeneous Schottky interface, however, the effective SBH described by Eq. (4) increases at higher temperatures. The underlying physical mechanism of this temperature dependence can be revealed by simply dividing the inhomogeneous interface into low SBH region and high SBH region. The ratio of the junction current through high SBH region over that through the low SBH region in thermionic emission theory is

\[ \exp\left(-\frac{q(\varphi_B^{high} - \varphi_B^{low})}{kT}\right), \quad \text{which increases at higher temperatures, consequently leading to the increase of the effective SBH.} \]

With a SBH which is temperature and bias dependent, the \( J-V \) behavior of a SBD in thermionic emission theory can be written as

\[ J = A^* T^2 \exp\left(-\frac{q\varphi_{B,(V,T)}^{I-V}}{kT}\right)\left[\exp\left(\frac{qV}{kT}\right) - 1\right]. \quad (5) \]

Equating Eqs. (1) and (5), the ideality factor \( n \) in the empirical equation can be obtained as
For a typical SBD of which the \( J-V \) curve follows Eq. (1), the ideality factor \( n \) is a constant as the inverse of the slope of the linear segment of the \( \ln(J)-V \) curve. Consequently, the dependence of \( \varphi_{B,(V,T)}^{J-V} \) on applied bias \( V \) should be linear. At temperature \( T \), Eq. (6a) can be written as,

\[
\frac{1}{n} - 1 = -\frac{\varphi_{B,(V,T)}^{J-V} - \varphi_{B,(0,T)}^{J-V}}{V} , \quad (6a)
\]

Here \( \rho_1 \) is a coefficient which is temperature dependent.

According to Eq. (4), the bias induced change of SBH can be written as,

\[
\Delta \varphi_{B,(V,T)}^{J-V} = \Delta \varphi_{B,(V,0)}^{\text{mean}} - \frac{\Delta \sigma_{(V,0)}^2}{2kT/q} , \quad \text{where} \quad \Delta \varphi_{B,(V,0)}^{\text{mean}} = \rho_2 V, \quad \Delta \sigma_{(V,0)}^2 = \rho_3 V , \quad (7)
\]

Here, \( \rho_2 \) and \( \rho_3 \) are temperature independent coefficients, representing the voltage dependences of the mean value and the standard deviation of the inhomogeneous Schottky junction, respectively. Combining Eq. (6b) and (7),

\[
n^{-1}(T) - 1 = -\rho_1(T) = -\rho_2 + \frac{\rho_3}{2kT/q} , \quad (8)
\]

Then, the physical meaning of the ideality factor \( n \) in the widely used empirical Eq. (1) is revealed as that it represents the voltage deformation of the barrier distribution at the inhomogeneous Schottky junction.

Figure 4(a) and 4(b) plot the extracted \( \varphi_{B,(0,T)}^{J-V} \) and \( n^{-1} - 1 \) of the Ni/AlN SBD as a function of the \( q/2kT \). A linear fitting of the \( \varphi_{B,(0,T)}^{J-V} \) data in Fig. 4(a) using Eq. (4) gives the mean value of the Schottky barrier height \( q\varphi_{B,(0,0)}^{\text{mean}} \) to be 2.105 eV with a standard deviation \( q\sigma_{(0,0)} \) of 0.235 eV at zero bias. A linear fitting of the \( n^{-1} - 1 \) data in Fig. 4(b) using Eq. (8) gives the voltage dependences of the mean Schottky barrier height and the standard deviation with the coefficients of \( \rho_2 = 0.277 \) and \( \rho_3 = -22.5 \text{ mV} \).

The mean Schottky barrier height extracted by analyzing the \( J-V \) characteristics is in good agreement with the reported charge neutral level (CNL) and the predicted values of SBHs of AlN SBDs.\textsuperscript{26-28} The positive value of \( \rho_2 \) indicates that the mean Schottky barrier height increases at
forward biases. The negative value of $\rho_3$ indicates that the standard deviation of the inhomogeneous Schottky junction decreases at forward biases, i.e., the junctions effectively becomes more uniform under forward biases. These are straightforward consequences when considering the image-force lowering at the metal-semiconductor interface.\textsuperscript{18} Besides, in an inhomogeneous Schottky junction, the low SBH region is usually ‘pinched-off’ by the surrounding high SBH region, leading to a pronounced band bending in the low SBH region.\textsuperscript{37} Under forward biases, it has been revealed by numerical simulations that the maximum point of the bended conduction band rises and also shifts from the interface towards the bulk region of semiconductor\textsuperscript{18,19,37} consequently resulting in the increase of the Schottky barrier height and also an relatively more uniform Schottky junction.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Plots of, (a) $\phi_{B, (0,T)}$, and (b) $(n^{-1} - 1)$ as a function of $q/2kT$.}
\end{figure}

The as-grown AlN crystal is $n$-type.\textsuperscript{14,15} Assuming a constant electron mobility in the temperature range studied, the conductance or inverse of resistance $(1/R)$ can be described as,$^2,15$

$$1/R \sim \exp \left( -\frac{E_D}{kT} \right)$$  \hspace{1cm} (9)

where $E_D$ is the activation energy of the donor level. The bulk resistances of the as-grown AlN crystal was estimated as the differential resistance from the current-voltage characteristics between the two ohmic contacts. An activation energy $E_D$ of 371 meV can be extracted from the slope of $\ln(1/R) - 1/T$ relation, as shown in Fig. 5. This value may be underestimated due to the inclusion of contact resistances. Oxygen impurities in the form of $O_N$ is the possible origin of the $n$-type conductivity in the PVT grown AlN single crystals.\textsuperscript{14,15}
FIG. 5. Arrhenius plot of $1/R$, where $R$ is the differential resistance at 10 V between the two ohmic contacts of the fabricated device.

![Arrhenius plot](image)

FIG. 6. (a) $C-V$ curve of the Ni/AlN SBD measured at 1 kHz at room temperature. (b) $1/C^2-V$ plot of the measured $C-V$ curve.

The SBH can also be estimated by conducting the capacitance-voltage ($C-V$) measurement. As the capacitance is mainly determined by the bulk properties of the semiconductor, the inhomogeneity of the Schottky interface plays little role in the estimation of SBH from the $C-V$ curve. Therefore, the value of $\Phi^L_B - V$ is expected to be close to that of $\Phi^\text{mean}_B$. To verify the validity of the inhomogeneity analysis of the AlN Schottky junction, we measured the $C-V$ curves of the Ni/AlN SBD. Figure 6(a) shows the $C-V$ curve measured at 1 kHz at room temperature. The donor concentration $N_D$ can be estimated from the $1/C^2-V$ plot shown in Fig. 6(b) through the equation,

$$\frac{d(1/C^2)}{dV} = -\frac{2}{q\varepsilon_0\varepsilon_r N_D}, \quad (10)$$

Here, $\varepsilon_0$ the is the vacuum permittivity, and $\varepsilon_r$ is the relative permittivity of AlN. The net donor
The concentration $N_D$ of the PVT grown AlN crystal was obtained to be $\sim 2.4 \times 10^{15}$ cm$^{-3}$. The electron density $n_e$ can be roughly estimated using a simplified charge neutrality equation,$^{15}$

$$n_e^2 = \frac{N_D N_C}{2} \exp\left(-\frac{E_D}{kT}\right), \quad (11)$$

Here, $N_C$ is the effective density of states in the conduction band. Taking the effective electron mass in AlN as $0.48 m_0$, where $m_0$ is the electron mass, $N_C$ was calculated to be $8.3 \times 10^{18}$ cm$^{-3}$.

The electron density $n_e$ can also be written as

$$n_e = N_C \exp\left(-\frac{E_F}{kT}\right), \quad (12)$$

Here, $E_F$ is the energy difference between the Fermi level and the conduction band minimum. Combining Eqs. (9)-(12), it can be calculated that $n_e = 7.9 \times 10^{13}$ cm$^{-3}$ and $E_F = 298$ meV. The intercept $V_0$ on voltage axis of the $1/C^2-V$ curve is about 1.95 V, as shown in Fig. 6(b). Through the following equation,$^{18}$

$$q\phi_B^{C-V} = qV_0 + kT + E_F, \quad (13)$$

the Schottky barrier height $q\phi_B^{C-V}$ can be obtained to be 2.27 eV, which is close to the mean Schottky barrier height $q\phi_B^{mean}$ (2.105 eV) obtained from the inhomogeneity analysis on the $J-V$ characteristics. This proves that the Ni-AlN interface is inhomogeneous and that the $J-V$ characteristics of the Ni/AlN SBD should be analyzed using an inhomogeneity model to reveal the intrinsic physical properties of the Schottky junction.

The inhomogeneity analysis explains the significant deviation of the relatively low SBH in $J-V$ characteristics of state-of-the-art AlN SBDs from the predicted SBH which is much larger due to the ultrawide bandgap and the large CNL level of AlN semiconductor. Figure 7 schematically illustrates the band diagrams of a Ni/AlN SBD. The large deviation of the $q\phi_B^{l-V}$ from the $q\phi_B^{mean}$ indicates that the $J-V$ behavior of the inhomogeneous Ni/AlN junction is dominated by that of the low SBH region. With advanced material quality and/or surface/interface engineering processes to suppress the low SBH formation in an inhomogeneous Schottky junction, AlN SBDs with larger effective SBHs in $J-V$ characteristics are procurable for high voltage rectification applications.
FIG. 7. Schematic band diagram of the inhomogeneous Ni/AlN Schottky barrier diode, with the intrinsic mean SBH of the barrier distribution and the effective SBH of $J-V$ characteristics illustrated. The inset schematically illustrates the bias deformation of the effective Schottky barrier height, i.e., the maximum point of the bended conduction band becomes higher and moves away from the interface into the bulk.

The physical meaning of the ideality factor $n$ in the empirical Eq. (1) is not straightforward but should be understood in form of $(n^{-1}-1)$ which representing the voltage deformation of an inhomogeneous Schottky junction. Here we introduce a factor $m$ which represents the voltage modification of the effective SBH in transport behaviors of an inhomogeneous Schottky junction, i.e., $\rho_1$ in Eq. (6). Then, the equation describing the $J-V$ curve, of which a linear segment can be identified in the ln($J$)-$V$ plot, of an inhomogeneous SBD can be re-written as following with parameters having explicit physical meaning in thermionic emission theory,

$$J = A^*T^2 \exp\left(-\frac{q(\phi_B^{J-V}(0,T) + mV)}{kT}\right) \left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

where $0 < m < 1$  \hspace{1cm} (14)

The extraction procedure of the parameters in Eq. (14) is the same as that in the empirical Eq. (1). The barrier distribution and its voltage deformation of the inhomogeneous Schottky junction can be revealed from the temperature dependences of $\phi_B^{J-V}(0,T)$ and $m(T)$, respectively.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Grant No. 61604098) and by the Shenzhen Science and Technology Innovation Commission (Grant Nos. JCYJ20170412110137562, JCYJ20170302143001451, and 20160520174438578) and also in part
by the Research Grants Council of the Hong Kong SAR under Grant Nos. 16302717 and C6013-16E. The authors thank Dr. Wei Zheng and Prof. Feng Huang from Sun Yat-Sen University for their assistance on measuring the room-temperature photoluminescence spectrum of the AlN using a 193 nm excimer laser.

References:

1. J. Y. Tsao, S. Chowdhury, M. A. Hollis, D. Jena, N. M. Johnson, K. A. Jones, R. J. Kaplar, S. Rajan, C. G. Van de Walle, E. Bellotti, C. L. Chua, R. Collazo, M. E. Coltrin, J. A. Cooper, K. R. Evans, S. Graham, T. A. Grotjohn, E. R. Heller, M. Higashiwaki, M. S. Islam, P. W. Juodawlkis, M. A. Khan, A. D. Koehler, J. H. Leach, U. K. Mishra, R. J. Nemanich, R. C. N. Pilawa-Podgurski, J. B. Shealy, Z. Sitar, M. J. Tadjer, A. F. Witulski, M. Wraback, and J. A. Simmons, Adv. Electron. Mater. 4, 1600501 (2017).

2. Y. Taniyasu, M. Kasu, T. Makimoto, Nature, 441, 325, (2006).

3. R. Rounds, B. Sarkar, A. Klump, C. Hartmann, T. Nagashima, R. Kirste, A. Franke, M. Bickermann, Y. Kumagai, Z. Sitar, App. Phys. Express 11, 071001 (2018).

4. T. Koppe, H. Hofsäss, U. Vetter, J. Luminescence 178, 267 (2016).

5. J. I. Pankove, T. D. Moustakas, chapter 1 in Semiconductors and Semimetals, 50, pp 1-10. Academic Press Inc. 1998, ISBN: 0080-8784 525.

6. U. K. Mishira, L. Shen, T. E. Kazior, and Y.-F. Wu, Proc. IEEE 96, 287 (2008).

7. K. J. Chen, O. Häberlen, A. Lidow, C. Tsai, T. Ueda, Y. Uemoto, Y.-F. Wu, IEEE Trans. Electron Devices 64, 779 (2017).

8. S. Nakamura, G. Fasol, and S. J. Pearton, The Blue Laser Diode: The Complete Story, 2nd ed. Berlin, Germany: Springer, 2000.

9. G. Selvaduray and L. Sheet, Materials Science and Technology 9, 463 (1993).

10. C. Hartmann, A. Dittmar, J. Wollweber and M. Bickermann, Semicond. Sci. Technol. 29, 084002 (2014).

11. W. Zheng, R. Zheng, F. Huang, H. Wu, F. Li, Photonics Res. 3, 38 (2015).

12. M. S. Sun, J.C. Zhang, J. Huang, J.F. Wang, and K. Xu, J. Crystal Growth 436, 62 (2016).

13. L. Jin, H. Zhang, R. Pan, P. Xu, J. Han, X. Zhang, Q. Yuan, Z. Zhang, X. Wang, Y. Wang, and B. Song, Nano Lett. 15, 6575 (2015).

14. Y. Irokawa, E. Villora, and K. Shimamura, Jpn. J. Appl. Phys. 51, 040206 (2012).

15. T. Kinoshita, T. Nagashima, T. Obata, S. Takashima, R. Yamamoto, R. Togashi, Y. Kumagai, R. chlessser, R. Collazo, A. Koukitu, and Z. Sitar, Appl. Phys. Exp. 8, 061003 (2015).

16. H. Fu, I. Baranowski, X. Huang, H. Chen, Z. Lu, J. Montes, X. Zhang and Y. Zhao, IEEE Electron Device Lett. 38, 1286 (2017).

17. H. Okumura, S. Suihkonen, J. Lemettinen, A. Uedono, Y. Zhang, D. Piedra, and T. Palacios, Jpn. J. Appl. Phys. 57, 04FR11 (2018).
18 Metal-Semiconductor Schottky Barrier Junctions and Their Applications, Edited by B. L. Sharma, Plenum Press, New York, 1984, pp. 1–56.

19 R. T. Tung, Mater. Sci. Eng. R 35, 1 (2001).

20 B. J. Baliga, Fundamentals of Power Semiconductor Devices, New York, NY, USA: Springer-Verlag, 2008.

21 S.N. Mohammad, Z. Fan, A.E. Botchkarev, W. Kim, O. Aktas, A. Salvador and H. Morkoç, Electronics Lett. 32, 598 (1996).

22 Z. Hu, K. Nomoto, B. Song, M. Zhu, M. Qi, M. Pan, X. Gao, V. Protasenko, D. Jena, and H. G. Xing, Appl. Phys. Lett. 107, 243501, (2015).

23 B. K. Li, X. Tang, J. N. Wang and K. J. Chen, Appl. Phys. Lett., 105, 032105 (2014).

24 A. Itoh, T. Kimoto, and H. Matsunami, IEEE Electron Device Lett. 16, 280 (1995).

25 V. Saxena, J. N. Su, and A. J. Steckl, IEEE Trans. Electron Devices 46, 456 (1999).

26 P. Reddy, I. Bryan, Z. Bryan, W. Guo, L. Hussey, R. Collazo, and Z. Sitar, J. Appl. Phys. 116, 123701 (2014).

27 P. Reddy, I. Bryan, Z. Bryan, J. Tweedie, S. Washiyama, R. Kirste, S. Mita, R. Collazo, and Z. Sitar, Appl. Phys. Lett. 107, 091603 (2015).

28 P. Reddy, I. Bryan, Z. Bryan, J. Tweedie, R. Kirste, R. Collazo, and Z. Sitar, J. Appl. Phys. 116, 194503 (2014).

29 J. H. Werner and H. H. Güttler, J. Appl. Phys. 69, 1522 (1991).

30 S. Chand and J. Kumar, J. Appl. Phys. 80, 288 (1996).

31 A. Gümüş, A. Türüt, and N. Yalçin, J. Appl. Phys. 91, 245 (2002).

32 Z. Tekeli, Ş. Altındal, M. Çakmak, S. Özçelik, D. Çalışkan and E. Özbay, J. Appl. Phys. 102, 054510 (2007).

33 Y. Taniyasu and M. Kasu, Appl. Phys. Lett. 96, 221110, (2010).

34 G. A. Slack, L. J. Schowalter, D. Morelli, and J. A. Freitas Jr., J. Crystal Growth 246, 287 (2002).

35 H.Z. Xu, A. Bell, Z.G. Wang, Y. Okad, M.Kawabe, I. Harrison, C.T. Foxon, J. Crystal Growth 222, 96 (2001).

36 Q. Yan, A. Janotti, M. Scheffler, and C. G. Van de Walle, Appl. Phys. Lett. 105, 111104 (2014).

37 J. P. Sullivan, R. T. Tung, M. R. Pinto, and W. R. Graham, J. Appl. Phys. 70, 7403 (1991).