Dominance of forward tunneling current in AlGaInP based heterostructures red light emitting diode

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In the present work we have measured the forward bias current-voltage (I-V) characteristics of AlGaInP based heterostructures red light emitting diode over a wide temperature range from 350 K to 77 K. The forward I-V characteristics show two distinctive regions below and above roughly 1.75 Volt marked by two different slopes, virtually insensitive to variation of temperature, which seems to suggest that the carrier transport process has complex character and there exist various tunneling mechanisms. The semilog plot of I-V curves exhibit two distinct, low and medium bias regions and the corresponding characteristic energies seem to suggest that there exist probable carriers which are electron and heavy hole respectively that undergoes change with bias voltage. This insight together with the data generated in the investigation will be helpful for device application.

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1. Introduction

It is needless to emphasize that there are many instruments used in the field of defence and space research programmes which make use of UV to IR radiation emission and detection. The performance of many of these instruments depends on the capabilities of the emitters and detectors under different operating conditions. It is expected that the performance of the sensing parts of these instruments should remain stable over a wide range of temperature which may alter from room temperature to temperatures far below and above it. It is found that the carrier transport and recombination mechanisms of different types of light emitting diodes (LEDs) drastically change with temperature. There is not enough study on the performance of the commercially available LEDs from room to very low temperature area. So, the data obtained from this study will be very useful to select the proper opto devices for fabricating and designing efficient instruments. One such high performance LED is AlGaInP-based LED.

AlGaInP-based LEDs have a broad wavelength spectrum from green to red and it is used widely as a light source for various applications of traffic signals, displays, indicators and general lightings at different ambient temperatures [1,2]. Recently the internal quantum efficiency of such LEDs has reached nearly 99%. But due to the substantial difference in the refractive indices between the quaternary epitaxial layers ($n \sim 3.3$ at 635 nm) and air ($n \sim 1$) the external quantum efficiency is still low [1,3]. Although AlGaInP-based LEDs have been successfully made, their junction properties have not yet been adequately examined. In such LEDs the electrical characterization can provide important information about the current transport through the wide band-gap p-n heterojunctions and layer materials. Such information of the carrier transport mechanisms is essential for achieving a fundamental understanding and further improvement of the device performance. In spite of the significant research efforts invested by many authors, these carrier transport mechanisms are still not well cleared. Several publications highlighting on the dominance of tunneling current in GaN based blue light emitting diodes (LEDs) are available [4-7]. These literatures show that the variation of ideality factor with temperature for all type of LEDs is not similar and their characteristic energies are also different. Many other workers have successfully applied this current transport model to explain the current transport process in different heterojunctions devices [8,9].

In this report, by studying the temperature dependent characteristics of forward tunneling current in AlGaInP-based LED, we try to find out the various mechanisms responsible for the variation of the same as a function of temperature and bias voltage. This investigation will be important for both physical understanding and practical applications.

2. Experimental details

In our investigation we used one AlGalnP-based red light emitting diode (LL2508JQHR4-A02, 100 deg.) procured from RS Components. The peak wavelength of the LED is 624 nm. The LED was placed inside a bath type optical cryostat designed in our laboratory [10]. With special care, liquid nitrogen was poured inside the cryogen chamber of the cryostat which was pre-evacuated to a pressure 10^{-4} Torr by using a high vacuum pumping unit (Model No. PU-2 CH-8, manufactured by Vacuum Products & Consultants) to avoid moisture on sample. The temperature measurement in the range 350 K to 77 K was done by using a Chromel-Alumel thermocouple (TC). The output of TC was recorded by a Keithley 2000 multimeter with accuracy of the order of ±0.14 K. I-V measurements were performed by Keithley 2400 source measure unit. The details of the experimental set up are being available in our previous work [11].

3. Results and discussion

3.1 Forward I-V characteristics

The forward I-V curves for AlGaInP-based LED are shown in Fig. 1. The most striking feature of forward I-V characteristics is the very weak temperature dependence of the slope of semilog I-V curves, in sharp contrast to the standard Shockley model of a p-n diode.

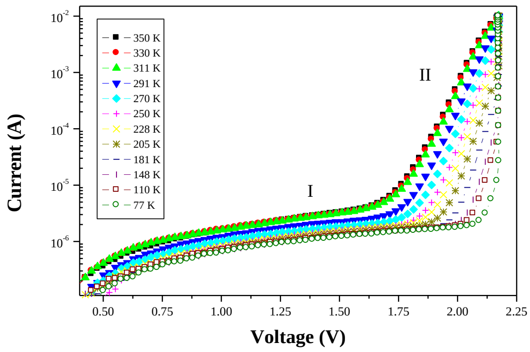

Fig. 1. Semilog I-V characteristics of AlGaInP-based light emitting diode in the temperature range 350-77 K. Marks I and II denote low bias and medium bias region respectively

The semilog I-V curves show two successive linearly dependent segments with different slopes which are dependent on the bias levels. The first segment is defined as low-bias (I) dominant at voltages lower than 1.75 V and the second segment as medium-bias (II) dominant above 1.75 V respectively. Both components can be well approximated by the exponential functions [6,12]

$$I_1 = I_{S1}[\exp(eV_j / E_1) - 1] \qquad V_j \geq 0 \qquad (1a)$$

$$I_2 = I_{S2}[\exp(eV_j / E_2) - 1] \qquad V_j \geq 0 \qquad (1b)$$

where, e is the electron charge, I_{S1}, I_{S2} are the pre-exponential factors and E_1, E_2 are the characteristic energies for low and medium bias level respectively. In general for a p-n diode the I-V characteristics can be expressed by $I = I_S\exp(eV/nkT - 1)$, where n is the ideality factor and K is the Boltzmann constant. When the value of n lies between 1 and 2, the current flow is mainly due to diffusion recombination current; while if n is larger than 2, tunneling current becomes dominant. If we assume the characteristic energies E_1 (= n_1KT) for low bias and E_2 (= n_2KT) for medium bias then these energies represent the tunneling transparency of the energy barrier at the junction interface. The values of the characteristic energies E_1, E_2 and ideality factors n_1, n_2 are obtained from our experimental results. Figure 2 shows a plot of the characteristic energies E_1, E_2 and ideality factors n_1, n_2 versus temperature from 350 K to 77 K.

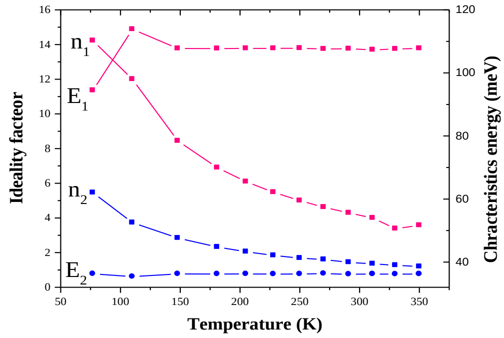

Fig. 2. The variations of the characteristic energies and ideality factors as a function of temperature

The variations of E_1 and E_2 with temperature are very small which indicates that the dominant transport mechanism is associated with tunneling of carrier rather than thermal diffusion.

3.2 Tunneling current through p-n junction

The weak temperature dependent slope of semilog I-V curves for the present LED, suggests the involvement of tunneling transport across the junction, and associated impurity-level radiation emission is an evidence of tunneling to those levels. The mechanism of ‘‘excess current’’ in heavily doped p-n junctions was considered by Morgan [13], where the bias-dependent shift of emission peak is usually observed. This type of process may occur in the space-charge region of the junction through one usually called diagonal tunneling or several intermediate (deep-center) states. Furthermore, the tunneling probability calculations, the forward-bias excess current involving deep levels was obtained in the following form [13]:

$$I \sim \exp\{\frac{-4\gamma}{3}[\frac{e(V_b - V)}{E_\mu}]^{3/2}\} \qquad (2)$$

Where

$$\gamma = [\frac{1+r}{(1+r^{1/3})^3}]^{1/2} \qquad (3)$$

equals very nearly one half of reasonable values of the mass ratio $r = m_l/m_n$, V_b is the built-in potential and E_μ is the bias-dependent characteristic tunneling energy, associated with the electric field in the junction. For an asymmetric step junction Eq. (2) may be rearrange in the same manner of Eq. (1), as

$$I = I_S[\exp(eV_j / E_T) - 1] \qquad V_j \geq 0 \qquad (4)$$

where, E_T is a characteristics energy constant, given by

$$E_T \approx \frac{4eh}{\pi}\left(\sqrt{\frac{N_1}{m_T^* \varepsilon_r \varepsilon_0}}\right) \qquad (5)$$

with N_I, the ionized impurity concentration, ε_r, the static dielectric constant, ε_0, the vacuum permittivity. The tunneling effective mass m_T^* is the reduced effective mass of light holes and electrons for an interband (diagonal) tunneling or effective mass of the carriers of one type for band-deep level tunneling [6]. The value of N_I estimated from C-V measurement (curve is not shown here) is equal to 8.3×10^{18} cm^{-3}. From Fig. 2 it is also clear that E_1 and E_2 remain almost unchanged with temperature which indicates that the temperature dependence of N_I is very weak. Therefore, from Eq. (5) it can be said that the value of E_T is directly related to m_T^*. On the other hand the nature of effective mass m_T^* may be ascertained from E_T. Assuming $\varepsilon_r \approx 12.04$ and m_T^* = $0.113m_0$ [14-16] we obtain E_{T1} = 107.7 mev, which is very close to the average experimental value of E_1 = 107.10 meV. Precisely, it seems reasonable to explain the low-voltage current component by electrons tunneling to deep defect levels on the p-side of the junction. In such electron tunneling process, electron releases its energy as phonons i.e. without contributing to light emission. Moreover, when electrons pass through deep defect levels on the p-side of the junction the output efficiency will decay, even though the input efficiency is quite high. In order to tentatively interpret the medium-bias current component that dominates at larger voltages (V > 1.75 V), we take m_T^* equal to the heavy hole effective mass = $0.712m_0$. This gives an estimate of E_{T2} = 42.90 meV, which also quite close to the average experimental value of E_2 = 36.15 meV. However, it may be mentioned that the estimations of E_1 and E_2 are less accurate than that of the theoretical value because of uncertainties associated with determination of the series resistance. Therefore, the medium-voltage component may be explained as a heavy hole tunneling into n-side, followed by the radiative transition via Al-related levels. There exists also an alternative possibility [6] that carriers are denoted by an effective mass of electron and light hole given by $m_T^* = 1/(1/m_e^* + 1/m_{lh}^*)$. Using the value of m_{lh}^* = $0.164m_0$, m_T^* turns out to be $0.0669m_0$ from which we can estimate the value of E_T = 139.97 meV. It is clearly found that this is much higher than the experimental value and as such this possibility is excluded. All the tunneling entities are listed in Table 1. It is also noted that the ratio of E_T in both bias regions should compare with the value $E_1/E_2 = (m_2^*/m_1^*)^{1/2}$ obtained from Eq. (5). Thus it is clear that the characteristic energies are inversely associated with the effective masses of the tunneling carriers. Our experimental results yields E_1/E_2 = 2.96. This value of the ratio of characteristic energies is consistent with the ratio of the square root of the effective masses for heavy holes and electrons (= 2.51). In our previous work [17] we found for GaAs based infrared emitter the low-bias component was explained as electron tunneling where the medium-bias component was explained by light hole tunneling. Therefore, the carriers involved in transport phenomena are different for different materials. However, the actual physical process of the change of tunneling entities from electrons to heavy holes with increasing bias is not well understood. The change of tunneling entities may be related to the layer structure and defect distribution within such device [4]. The flow of the carriers in such device is schematically illustrated in Fig. 3

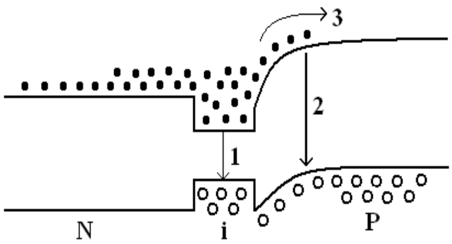

Fig. 3. Energy band diagram of conventional LEDs showing three main carrier transport modes. Arrow 1, the radiation recombination in the active region; arrow 2, the non-radiation recombination in the indirect band-gap AlInP confinement layer; arrow 3, carrier leakage and overflow

Table 1. Analysis of tunneling entities in LL2508JQHR4-A02 device

Bias range (V)	Experimental value of characteristic energy (meV)	Theoretical value of characteristic energy (meV)	Effective mass	Nature of carrier
0.85–1.75	107.10	107.7	$0.113m_0$	Electron
1.75–2.15	36.15	42.90	$0.712m_0$	Heavy hole

4. Conclusion

In conclusion, the measurement of the forward I-V characteristics for LL2508JQHR4-A02 LED shows that the slope of the exponential curve changes relatively slowly as a function of temperature which indicates the involvement of various mechanisms including tunneling responsible for transport. Also in semilog I-V characteristics we can identify low-bias and medium-bias exponential components where the low-voltage current component by electrons tunneling to deep defect levels on the p-side of the junction and in such electrons tunneling process, electron release its energy as phonon and the medium-bias component may be explained by tunneling of heavy hole tunneling into n-side, followed by the radiative transition via Al-related levels. Generally, the light intensity emitted by various LEDs is found to increase with lowering of temperature. In this case tunneling of heavy hole is much dominant in the process of radiative transition. This understanding of the device properties will be important for the purpose of application.

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References

[1] H. K. Lee, D. H. Lee, Y. M. Song, Y. T. Lee, J. S. Yu, Solid-State Electronics **56,** 79 (2011).
[2] M. S. Kim, H. K. Lee, J. S. Yu, Semicond. Sci. Technol. **28,** 025005 (2013).
[3] C. H. Yen, Y. J. Liu, K. H. Yu, Research Express@NCKU **23,** 1 (2013).
[4] D. Yan, H. Lu, D. Chen, R. Zhang, Y. Zheng, Appl. Phys. Lett. **96,** 0835041 (2010).
[5] H. C. Casey, J. Muth, S. Krishnankutty, J. M. Zavada, Appl. Phys. Lett. **68,** 2867 (1996).
[6] P. G. Eliseev, P.Perlin, J. Furioli, P. Sartori, J. Mu, M. Osinski, Journal of Electronics Materials **26,** 311 (1997).
[7] D. W. Yan, Z. M. Zhu, J. M. Cheng, X. F. Gu, H. Lu, Chin. Phys. Lett. **29,** 087204 (2012).
[8] A. Zemel, D. Eger, Solid-Slate electronics **23,** 1123 (1980).
[9] G. Sarusi, A. Zemel, A. Sher, D. Eger, J. Appl. Phys. **76,** 4420 (1994).
[10] N. B. Manik, A. N. Basu, S. C. Mukherjee, Cryogenics **40,** 341 (2000).
[11] P. Dalapati, N. B. Manik, A. N. Basu, Journal of Semiconductors **34,** 092001 (2013).
[12] C. L. Reynolds, A. Patel, J. Appl. Phys. **103,** 0861021 (2008).
[13] T. N. Morgan, Phys. Rev. **148,** 890 (1966).
[14] www.semiconductors.co.uk/propiiiv5653.htm
[15] N. C. Chen, C. M. Lin, C. Shen, W. C. Lien, T. Y. Lin, Optics Express **16,** 20759 (2008).
[16] J. Rennie, M. Okajima, M. Watanabe, G. I, Hatakoshi, IEEE J. Quant. Elec. **29,** 1857 (1993).
[17] P. Dalapati, N. B. Manik, A. N. Basu, Front. Optoelectron. **7,** 501 (2014).

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