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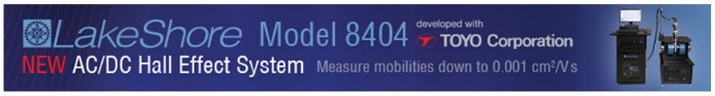

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Recombination mechanisms and band alignment of $GaAs_{1-x}Bi_x$/GaAs light emitting diodes

N. Hossain,[1] I. P. Marko,[1] S. R. Jin,[1] K. Hild,[1] S. J. Sweeney,[1,a)] R. B. Lewis,[2,3]
D. A. Beaton,[2] and T. Tiedje[3]
[1]*Advanced Technology Institute and Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[2]*Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1 Canada*
[3]*Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC V8W 3P6, Canada*

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We investigate the temperature and pressure dependence of the light-current characteristics and electroluminescence spectra of $GaAs_{1-x}Bi_x$/GaAs light emitting diodes. The temperature dependence of the emission wavelength shows a relatively low temperature coefficient of emission peak shift of 0.19 ± 0.01 nm/K. A strong decrease in emission efficiency with increasing temperature implies that non-radiative recombination plays an important role on the performance of these devices. The pressure coefficient of the $GaAs_{0.986}Bi_{0.014}$ bandgap is measured to be 11.8 ± 0.3 meV/kbar. The electroluminescence intensity from GaAsBi is found to decrease with increasing pressure accompanied by an increase in luminescence from the GaAs cladding layers suggesting the presence of carrier leakage in the devices. *© 2012 American Institute of Physics*. [doi:10.1063/1.3681139]

The ternary alloy $GaAs_{1-x}Bi_x$ has attracted increasing interest in recent years due to the large band gap reduction with relatively small concentrations of Bi[1,2] (~88 meV/% Bi), which makes it a promising material for optoelectronic applications in the near and mid-infrared spectral range.[3] Furthermore, these GaAs-based alloys are compatible with AlGaAs/GaAs distributed-Bragg reflectors, which are well established in vertical cavity surface emitting lasers (VCSELs) and related devices. Despite the difficulties to incorporate Bi into the GaAs lattice,[4,5] $GaAs_{1-x}Bi_x$ layers with $x \sim 10\%$ have been grown using molecular beam epitaxy (MBE) techniques.[6] The spectroscopic data reported to date show promising optical properties in this material.[7,8] Strong photoluminescence (PL) and electroluminescence (EL) from $GaAs_{1-x}Bi_x$ light emitting diodes (LEDs) have been reported.[9] However little, if any, research has been undertaken to assess the carrier recombination and temperature dependent processes occurring in such devices. The determination of the alignment of conduction and valence bands at the $GaAs_{1-x}Bi_x$/GaAs interface is critical for theoretical modeling and design optimization. Type-I band alignment provides an increased optical gain due to better electron-hole overlap. On the other hand, type-II band alignment could potentially allow access to longer wavelengths.[10] The band alignment of the GaAsBi/GaAs interface remains uncertain with reports in the literature of type-I,[11,12] type-II,[13] and a nearly flat[14] conduction band offset. In this letter, we investigate the carrier recombination processes of $GaAs_{1-x}Bi_x$/GaAs LEDs to aid in the design and optimization of device structures. Using high hydrostatic pressure and low temperature techniques, we have probed the processes that limit the device performance. The pressure and current dependence measurements also provide evidence for the band alignment at the $GaAs_{1-x}Bi_x$/GaAs interface.

The devices in this study were grown in a VG-V80H MBE system on n-doped (001) GaAs substrates. The active region consists of a 50 nm $GaAs_{0.986}Bi_{0.014}$ layer between two 25 nm GaAs spacer layers. The entire active region is sandwiched between a 1000 nm p-doped and a 1000 nm n-doped GaAs buffer layers. Further details of the growth and processing of similar devices can be found in Ref. 9. Temperature dependence measurements over the range of 80–260 K were performed using an Oxford Instruments gas exchange cryostat. At each temperature, an emission spectrum at a fixed current density ($J = 124$ A cm^{-2}) and the light output intensity versus current were measured. Hydrostatic pressure measurements were carried out on the devices at 80 K and 120 K up to 6 kbar in order to indentify the origin of loss processes in the devices.

The emission wavelength of the device is measured to be ~936 nm at 260 K. Figure 1 shows the temperature

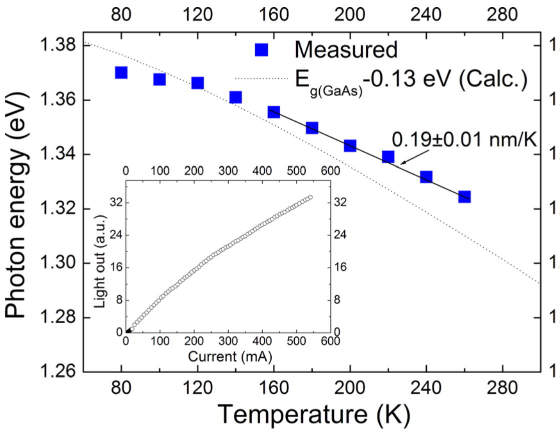

FIG. 1. (Color online) Temperature dependence of the measured EL emission peak. L-I characteristics at 80 K (inset).

[a)] Author to whom correspondence should be addressed. Electronic mail: s.sweeney@surrey.ac.uk.

dependence of the EL peak, which shifts with temperature at the rate of -0.30 ± 0.01 meV/K (calculated by a linear fit) corresponding to the wavelength change of 0.19 ± 0.01 nm/K over the temperature range 160-260 K. From the measured temperature dependence of the EL peak (in Fig. 1), we do not observe the typical strong "S"-shape behaviour down to 80 K due to the localization effect as observed by others.[7,15] Under higher carrier injection, localisation effects may be screened compared with much lower injection photoluminescence studies. The temperature dependence of the fundamental energy gap of GaAs, E_g(GaAs) is obtained from the well-known Varshni equation (given in Fig. 1)[16]

$$E_g(T) = E_0 - \alpha T^2/(T + \beta), \tag{1}$$

where E_0 (1.519 eV (Ref. 17)) is the band gap at $T = 0$ K, and α (0.54 meV/K (Ref. 17)), β (204 K (Ref. 17)) are the Varshni parameters. The temperature dependence of the band gap of GaAs determined by the Varshni parameters is given in Fig. 1 with a negative vertical offset of -0.13 eV for comparison purposes. It shows that the EL peak of the GaAsBi devices shifts less with increasing temperature than the band gap of GaAs. This behavior is consistent with previous photoluminescence measurements[7] and may be attributed to a valence band anti-crossing effect.[12]

Fig. 2 shows the change in efficiency as a function of temperature for a forward bias current density of 373 A/cm^2. A rapid decrease in efficiency with increasing temperature in these devices implies that some non-radiative loss mechanism(s) is (are) activated at higher temperature. The light-current characteristics show a sub-linear behavior (inset of Fig. 1) even at temperatures as low as 80 K which indicates a presence of a loss mechanism with a stronger carrier density (n) dependence than the radiative current.[18] Since carrier leakage has an approximately exponential dependence on n, this may suggest that carrier leakage plays an important role in these devices, if, as expected, Auger recombination is negligible in these short wavelength devices.

To further probe the recombination mechanisms, high pressure techniques were utilized. The application of hydrostatic pressure mainly affects the conduction band (CB) causing an increase in the direct band gap of III-V semiconductors and is, therefore, an ideal method to investigate the important band gap dependent non-radiative processes. Fig. 3 shows the EL spectra (on a log scale) as a function of pressure for a forward bias current density of 124 A/cm^2 at 80 K. The decrease in overall EL emission intensity together with increased (relative to the GaAsBi) emission from the GaAs layers with increasing pressure (see Fig. 3) suggests the presence of a carrier leakage path in these devices, where the leakage activation energy (ΔE) decreases with increasing pressure (since dE/dP(GaAsBi) > dE/dP(GaAs), as shown in the inset of Fig. 3). The pressure (P) dependence of the leakage current density, J_{leak}, can be written simply as[18]

$$J_{leak}(P) = J_{leak}(0)\exp\left(-\frac{d\Delta E}{dP}\frac{P}{k_b T}\right), \tag{2}$$

where k_b is Boltzman's constant, T is the absolute temperature, and $J_{leak}(0)$ is the leakage current at atmospheric pressure. The pressure dependence of the higher energy emission peak corresponding to GaAs was obtained from a Gaussian fit to the measured EL spectra at 80 K (an example of such a fit is shown in the inset of Fig. 4). The integrated intensity (normalized at 0 kbar) of the GaAs emission as a function of pressure is shown in Fig. 4. The pressure coefficient for the $GaAs_{0.986}Bi_{0.014}$ Γ minimum (taken from the EL spectra and shown in inset of Fig. 3) is measured to be $dE_{\Gamma(GaAsBi)}/dP = 11.8 \pm 0.3$ meV/kbar and the pressure coefficient of the Γ minimum of GaAs is well known ($dE_{\Gamma(GaAs)}/dP = +10.7$ meV/kbar),[17] which gives $d\Delta E/dP = -1.1$ meV/kbar. Substituting this value into Eq. (2) yields the solid line shown in Fig. 4. As one can see, this provides an excellent agreement with the experimental data confirming that carrier leakage into GaAs barriers is occurring in these devices. We note that the GaAsBi emission energy has a higher pressure dependence than that for GaAs but a lower temperature dependence of the band gap. In the temperature dependence, we measure the effects both in the CB and valence band (VB), where localization near the VB edge may play a key

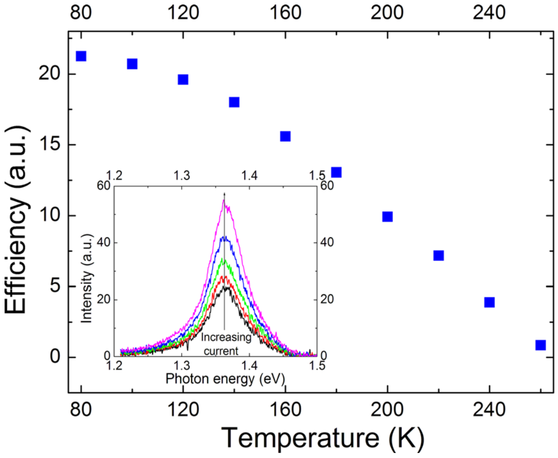

FIG. 2. (Color online) Emission efficiency as a function of temperature. Current dependence of EL emission for current 20–100 mA with 20 mA step (inset).

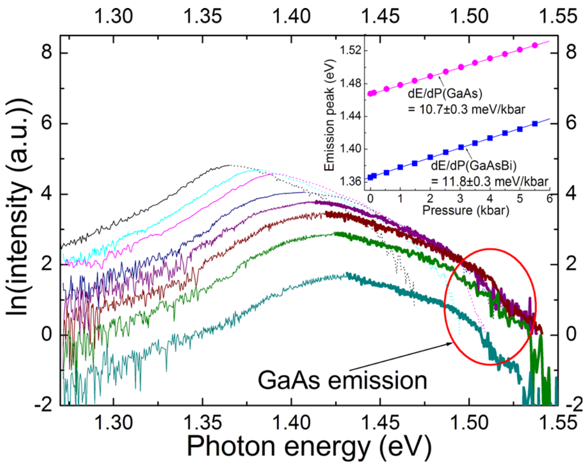

FIG. 3. (Color online) Pressure dependence of the natural log of measured EL emission spectra for pressure 0–6 kbar at 80 K. It shows a relative increase in GaAs emission with increasing pressure compared to GaAsBi emission. GaAsBi (measured) and GaAs (fitted) emission peaks as a function of applied pressure (inset).

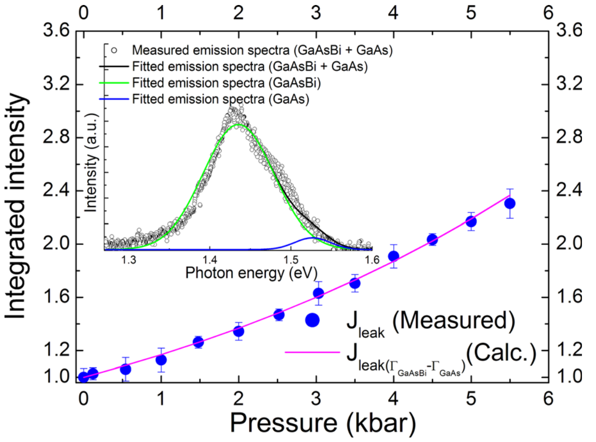

FIG. 4. (Color online) The integrated intensity (normalized at 0 kbar) of fitted GaAs emission as a function of pressure. An example fit is shown in the inset.

role for lower temperature dependence.[11] On the other hand, pressure mainly affects the CB, less influenced by Bi. There is no evidence of blue shift with increasing current injection (inset of Fig. 2) in this material at atmospheric temperature and pressure as would typically be the case for a type II material, such as $GaAs_{0.57}Sb_{0.43}$/GaAs.[19] Moreover, in case of type II band alignment at the $GaAs_{1-x}Bi_x$/GaAs interface, we would expect the pressure co-efficient of the emission wavelength to be same as GaAs (+10.7 meV/kbar) since the emission would then originate from GaAs CB to GaAsBi VB, hence a pressure co-efficient of +10.7 meV/kbar would be expected. Also, with increasing pressure, a relative increase in GaAs emission compared to GaAsBi emission suggests that the band offset for electrons reduces with increasing pressure, which leads to an increased carrier escape and subsequent radiative and non-radiative recombination outside the active region. Hence, we conclude that the higher pressure co-efficient of GaAsBi compared to GaAs coupled with an increase in emission from the GaAs cladding region with increasing pressure is consistent with a type-I band alignment at the $GaAs_{1-x}Bi_x$/GaAs interface.

In summary, it is found that the temperature dependence of the $GaAs_{0.986}Bi_{0.014}$ emission wavelength shows a low temperature coefficient of the emission peak of 0.19 ± 0.01 nm/K. A rapid decrease in the emission efficiency with increasing temperature implies that nonradiative recombination becomes dominant at higher temperature. An increase in emission from GaAs barriers with increasing pressure confirms the presence of a carrier leakage process in these devices. A current-independent emission energy, and higher pressure co-efficient of GaAsBi compared to GaAs coupled with an increase in emission from GaAs cladding region with increasing pressure is consistent with a type-I band alignment at the $GaAs_{1-x}Bi_x$/GaAs interface.

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