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Efficiency-limiting processes in Ga(NAsP)/GaP quantum well lasers

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We report on the carrier recombination mechanisms in dilute nitride Ga(NAsP)/GaP quantum well lasers. Spontaneous emission measurements show that defect-related recombination in the devices is less significant compared with other GaAs-based dilute nitride lasers. From temperature dependent measurements, we find that the threshold current density, J_{th} is dominated by non-radiative recombination process(es), which account for at least 91% of J_{th} at room temperature. The characteristic temperature, T_0 (T_1) is measured to be ~104 K (~99 K) around 200 K, which drops to ~58 K (~37 K) around room temperature. Hydrostatic pressure measurements reveal a strong increase of threshold current with increasing pressure. This implies that current leakage dominates carrier recombination which is also responsible for their low T_0 and T_1 values at room temperature. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4733312]

The dominance of silicon as a low cost material for electronic circuit applications has led to a desire to combine the advantages of optical data processing with the mature silicon microelectronics technology.[1] This merging of technologies is essential to keep up with the ever increasing need for bandwidth in optical inter- and intra-chip connections.[2] The significance of this emerging technology has made it an active area of investigation within both the industrial[3,4] and academic sectors.[5–7] However, the key challenge using silicon as a monolithic integration platform is the lack of a silicon based laser. The indirect band gap of silicon causes inefficient light emission. On the other hand, the large lattice mismatch between silicon and conventional III/V laser materials like GaAs (Refs. 8 and 9) or InP (Ref. 10) leads to difficulties in growing defect-free or threading-dislocation-free laser materials on silicon substrates. The quaternary dilute nitride Ga(NAsP) material shows a direct electronic band gap, efficient optical gain,[11] and a lattice constant similar to that of silicon,[12] and is promising for the lattice-matched growth of lasers based upon this material on silicon substrate. Recently, lasing operation at room temperature (RT) in Ga(NAsP)/GaP quantum well (QW) laser has been demonstrated.[13] However, the large J_{th} in these devices needs to be better understood in order to optimize and improve the device performance. In this letter, we investigate different carrier recombination processes in Ga(NAsP)/GaP QW lasers to aid in the design and optimization of device structures. Using high pressure and low temperature techniques, we have probed the processes that limit the device performance.

The devices in this study were grown by metal-organic vapor-phase epitaxy (MOVPE) on a GaP substrate. The active region of the device consists of a single 6.2 nm-thick $Ga(N_{\sim 5\%}As_{\sim 92\%}P)$ quantum well (SQW) within two undoped 200 nm GaP barrier/separate confinement layers. They are embedded in between 1.5 μm-thick n-$(Al_{23\%}Ga_{77\%})$P and p-$(Al_{23\%}Ga_{77\%})$P layers. 300 nm-thick n-GaP and 100 nm-thick p-GaP layers were grown as buffer and contact layers, respectively. Further details of the MOVPE growth process can be found elsewhere.[14] Broad-area laser structures were processed by depositing 50 and 100 μm wide Au/Cr metal stripes on the p-contact layer with Au/AuGe/Cr-based back n-contacts. These broad area devices were measured as-cleaved with cavity length of 1000 μm under pulsed operation (10 kHz repetition rate, 0.5% duty cycle) in order to reduce current heating effects.

Temperature dependent measurements over the range of 60–295 K were performed by using a closed-cycle cryostat set-up. At each temperature, both facet emission and spontaneous emission (SE) of the laser devices as a function of applied current were measured to quantify the threshold current and its radiative and non-radiative components. The spontaneous emission was collected through a window milled in the substrate of the devices using an optical fibre. Hydrostatic pressure measurements were performed on these devices at 80 K, 220 K, and RT from 0 to 7 kbar.

At RT J_{th} of the device is measured to be 4.3 ± 0.3 kA/cm^2 with a lasing wavelength of ~981 nm, much lower than the previously reported value of ~42 kA/cm^2 at a lasing wavelength of ~942 nm at 278 K for similar devices.[15] This indicates a significant improvement in device quality as reported recently.[13] However, this value of J_{th} is still considerably larger than more established GaAs-based lasers operating at similar wavelengths for which J_{th}/QW ≈ 100–200 A/cm^2.[16] Therefore, an understanding of the physical properties of these devices is essential. Fig. 1 shows the measured temperature dependence of the threshold current and external differential quantum efficiency, η_d, (inset) which yields the characteristic temperatures T_0 (derived from $1/T_0 = d\ln J_{th}/dT$) and T_1 (derived from $1/T_1 = -d\ln \eta_d/dT$), respectively. The various recombination processes (defect, radiative, Auger, and carrier

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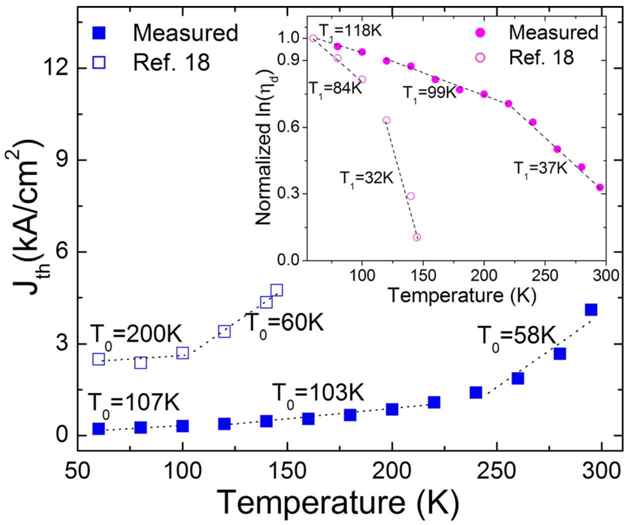

FIG. 1. J_{th} and ln[η_d] (inset) as a function of temperature.

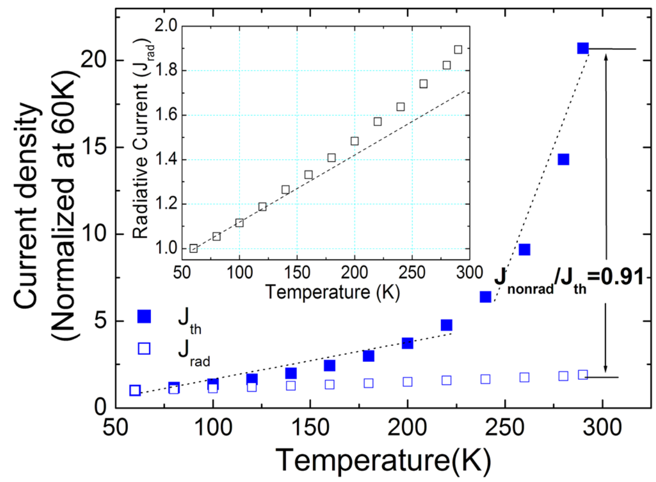

FIG. 2. Temperature dependence of J_{th} and J_{rad}. The J_{rad} has super linear temperature dependence (inset).

leakage) which contribute to the total threshold current have different temperature dependencies, and hence T_0 provides a tentative indication of the dominant recombination process in the semiconductor lasers. For an ideal quantum well laser, T_0(defect) $= 2T/3$, T_0(radiative) $= T$, and T_0(Auger or leakage) $\leq T/3$. Further details of these dependencies can be found in Ref. 17. T_0 is measured to be ~107 K around 100 K in these devices suggesting radiative dominated recombination at this temperature compared with $T_0 = 200$ K around 100 K for previously reported similar devices in Ref. 18. This unusually large T_0 is an indication of inhomogeneities in the active region and a non-thermal carrier distribution, as described in Ref. 19. This suggests that improvements in the material quality cause significant performance improvement in the current devices compared to the similar devices reported in Refs. 15 and 18. At RT, T_0 drops to ~58 K suggesting the presence of a carrier leakage path in these devices (since Auger recombination is expected to be weak at this short wavelength[18]). The inset of Fig. 1 shows that $T_1 \sim 99$ K at 200 K, decreasing to ~37 K at RT. T_1 in these devices shows similar behavior to the devices reported in Ref. 18, as shown in the inset of Fig. 1. Indeed, when compared with other devices operating at similar wavelengths,[18] T_1 is significantly lower in Ga(NAsP)/GaP devices suggesting that optical or recombination losses are important in these devices. We note that, at low temperature (100 K), taken alone, the T_0 value suggests dominant radiative recombination. However, since T_1 is low (118 K), this suggests that the coupled effects of carrier localization and non-radiative recombination (such as carrier leakage) at this temperature which, on average, give rise to $T_o \sim T$ at this temperature.

Fig. 2 shows the normalized (at 60 K) temperature dependence of J_{th} and its radiative component (J_{rad}) extracted from the SE measurements at laser threshold. Here, J_{rad} is determined by assuming that (a) J_{rad} is proportional to the integrated spontaneous emission rate at laser threshold and (b) that non-radiative recombination is negligible at the lowest temperature. J_{rad} therefore provides a measure of the maximum radiative component of J_{th} as a function of temperature. It is found that J_{rad} has a super-linear temperature dependence (inset of Fig. 2) unlike an ideal QW laser.[20] This implies that some optical loss process is present which increases with increasing temperature in these devices. From the measured J_{th} and J_{rad}, we estimate that the non-radiative contribution accounts for at least ~91% of J_{th} at 290 K. Thus, non-radiative processes dominate J_{th} near RT and non-radiative processes in these devices are reduced compared with the previously reported similar devices in Ref. 18, which is consistent with the improvement in threshold current density in these devices. We note that, the estimated maximum value of J_{rad} is 223 ± 3 A/cm^2 at 60 K (~422 ± 5 A/cm^2 at RT), which is rather high suggesting that this analysis may overestimate J_{rad} at low temperature due to there being another non-radiative recombination channel active at low temperature. Considering this non-radiative recombination (at 60 K) in our analysis, the non-radiative contribution at RT will be higher than ~91% as discussed later in this paper. To gain further understanding of the recombination processes in the devices, we analysed the SE using the "Z"-analysis.[21] Z represents the power law dependence of the current on carrier density where values correspond to: $Z=1$ (defect-related recombination), $Z=2$ (radiative recombination), $Z=3$ (Auger recombination), and $Z \geq 3$ (carrier leakage[22]). The measured Z_{th} of Ga(NAsP)/GaP devices as a function of temperature is displayed in Fig. 3. Z_{th} increases from 2.2 at 60 K to 3.5 at 290 K. The value of Z remains ~2.2 over a wide current range to laser threshold at low temperatures. There is no indication of significant defect ($Z=1$) at low current (down to $I_{th}/5$) unlike that observed in GaInAsN/GaAs dilute nitride lasers where Z approaches 1.6 at $I_{th}/5$,[19] indicating that defects are *relatively* less important in these devices. This indicates that improved material quality has enhanced the performance of these devices compared to earlier devices, as reported in Refs. 15 and 18. The value of $Z_{th} \geq 3$ at higher temperatures is consistent with the presence of carrier leakage path in these devices.

Fig. 4 shows the measured pressure dependence of J_{th} at 80 K, 220 K, and RT. Also, shown is the ideal expected variation of the radiative current, $J_{rad} \propto E_g^2$,[23] where E_g is the band gap taken here to be equal to the lasing energy. The pressure

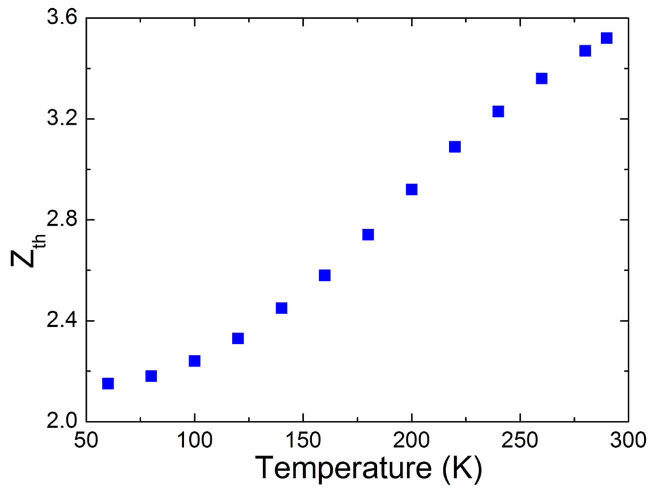

FIG. 3. Z_{th} as a function of temperature.

coefficient for the band gap of the devices is measured to be ~5.1 meV/kbar. We note that, pressure co-efficient of Γ minima in this $Ga(N_{\sim5\%}As_{\sim92\%}P)$ material is significantly lower than that of GaAs (+10.7 meV/kbar (Ref. 24)) and GaP (+11.2 meV/kbar (Ref. 24)) due to the band anti-crossing effect, which is explained in further detail in Ref. 18. It can be clearly seen that the threshold current increases with pressure much faster than J_{rad}, which suggests that the lasers are not operating in a radiatively dominated regime. The threshold current of the device increases by ~45% and ~100% up to 7 kbar at 80 K and 220 K, respectively. Also, an ~70% increase in threshold current is observed up to 2.5 kbar at RT (in these devices, at RT the highest pressure that a threshold current could be measured was 2.5 kbar, due to the upper limit of the pulsed voltage source). The rapid increase in threshold current with pressure indicates the presence of carrier leakage. In a simple model, the pressure (P) dependence of the leakage current, J_{leak}, can be written as:[18,25]

$$J_{leak}(P) = J_{leak}(0)\exp\left(-\frac{d\Delta E}{dP}\frac{P}{k_b T}\right) \tag{1}$$

where k_b is the Boltzmann constant and ΔE the leakage activation energy. The corresponding pressure dependence of J_{th} is given by:

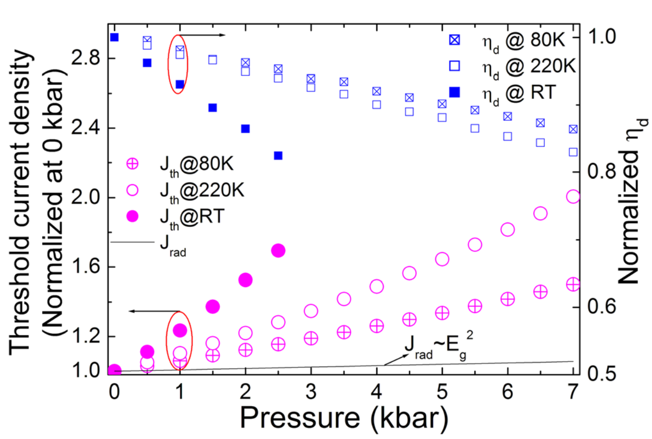

FIG. 4. Pressure dependence of the measured J_{th}, η_d and ideal expected variation of J_{rad} (calculated).

$$\frac{J_{th}(P)}{J_{th}(0)} = k_{rad}\frac{J_{rad}(P)}{J_{rad}(0)} + (1-k_{rad})\frac{J_{leak}(P)}{J_{leak}(0)} \tag{2}$$

where $k_{rad} = J_{rad}(0)/J_{th}(0)$, the radiative current proportion of J_{th} at ambient pressure where we assume that all other non-radiative recombination processes are negligible. As shown in Eq. (1), the decrease of the activation energy leads to the increase of current leakage with increasing pressure. From Fig. 2, $J_{rad}(0)/J_{th}(0)$ in these devices is found to be ~91%, ~33%, and ~9% at 80 K, 220 K, and RT, respectively. From the fit to the pressure data by using Eq. (2), we can then determine $d\Delta E/dP$, which are −2.9, −2.8, and −5.7 meV/kbar at 80 K, 220 K, and RT, respectively. The rate of increase of the band gap with pressure is measured to be +5.1 meV/kbar. Assuming that the conduction band quasi-Fermi level has a similar pressure dependence as the band gap, this results in a pressure coefficient for the leakage levels of +2.2, +2.3, and −0.6 meV/kbar at 80 K, 220 K, and RT, respectively. Hence, the leakage level has a smaller pressure dependence than the X minima of the GaP barrier (−1.5 meV/kbar (Ref. 24)). This suggests that the leakage into the X minima of the indirect GaP barrier is not significant in these devices. Despite the fact that a strong increase in threshold current with pressure is observed this may indicate that the leakage path involves states with a weaker pressure dependence, such as localized defect states in these devices. The calculated pressure coefficient for the leakage levels also suggests that carrier leakage is similar in the temperature range of 80–220 K but increases rapidly at RT. On the other hand, the differential efficiency drops at a higher rate with increasing pressure at higher temperature (as shown in Fig. 4) suggesting optical losses in the devices at higher temperatures. This is also consistent with the low T_1 at RT and superlinear behavior of J_{rad} with increasing temperature in the devices. However, this analysis is based on the assumption that all other non-radiative recombination processes are negligible at low temperature as discussed earlier in this paper. As an alternative hypothesis, we assumed that the carrier leakage process in these devices has the same pressure dependence at all temperatures with a value as given by the RT coefficient of -5.7 meV/kbar. Substituting this value in Eqs. (1) and (2), we find a k_{rad} ~ 82% at 80 K, which suggests the presence of additional non-radiative recombination at low temperature, which was neglected in the analysis of Fig. 2. By taking into account this additional non-radiative process(es) in the analysis of Fig. 2, our estimated non-radiative contribution increases slightly from ~91% to ~94% at 290 K and we estimate that the non-radiative processes in these devices compared to devices in Ref. 18 have reduced by ~14% at 160 K. These results show that the possible over estimation of the radiative current at low temperature (60 K) does not affect our analysis significantly. Hence, we conclude that carrier leakage due to the localized defect states dominates the recombination process up to 220 K, whereas optical losses in conjunction with carrier leakage dominate the recombination process near RT. The exact origin of these optical losses remains the subject of further investigation.

In summary, improved lasing characteristics in direct band gap Ga(NAsP)/GaP QW lasers has been observed. The threshold current of the devices is dominated by non-radiative recombination at RT. The non-radiative process is also responsible for the poor temperature sensitivity of the devices resulting in low T_0 values at RT. From pressure dependence measurements, we observe an increase in threshold current with increasing pressure, consistent with a carrier leakage path, which is believed to involve localized defect states and, at higher temperature, optical losses in the devices. If these processes can be reduced, the integration of Ga(NAsP)/GaP QW on silicon substrate may lead to a commercial solution for the monolithic integration of long term stable laser diodes to be used in silicon microelectronics technology.

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