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Temperature dependence of droop onset in optically pumped intrinsic InGaAs/InP heterostructures

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Although conventional III-V compound semiconductors are often considered not to exhibit an efficiency droop, a pronounced low temperature droop was recently measured in AlGaInP/GaAs multi-quantum well structures. In this work, we investigate the efficiency droop in simple optically pumped lattice matched InGaAs/InP single well heterostructures to exclude charge transport related effects from the measurements. The results show that droop is present in this very simplistic setup and, furthermore, starts approximately at the same carrier density as in typical III-N structures. Our results suggest that in its most fundamental form, droop can be explained by Auger-like processes. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4794404]

The research of the efficiency and related properties of conventional III-V materials has nearly halted during the last two decades due to the overwhelming interest received by the III-N materials. However, recent progress in optical refrigeration by laser cooling of solids[1,2] and electroluminescence[3,4] shows that better understanding of the factors affecting the efficiency of the conventional III-V compound semiconductors could greatly assist in developing optical cooling techniques. Furthermore, the readily available lattice matched and essentially non-polar III-V materials provide an attractive baseline for the properties of the III-N material system as well. This baseline for the droop was very recently established by measuring the temperature dependence of the efficiency droop in AlGaInP/GaAs multi-quantum well (MQW) structures, revealing an unexpected temperature dependence where the onset of droop moved towards lower excitation as the temperature was decreased, suggesting that the observed droop would not be caused by Auger-like recombination.[5] The efficiency droop in III-N materials has been given several explanations[6–8] during the last decade, but apart from the above experiment, few measurements involving the effect in conventional III-Vs have been made. In this letter, we simplify the experimental setup to the extreme and measure the droop and its temperature dependence in undoped lattice matched InGaAs/InP structures using optical pumping. We also compare our results with the droop in III-Ns and find that the droop in our setup starts at roughly the same excitation density as in typical III-N structures.

The lattice matched InGaAs/InP samples were fabricated on semi-insulating InP substrates in a horizontal metal organic vapor phase epitaxy (MOVPE) reactor at atmospheric pressure using trimethylindium (TMIn) trimethylgallium (TMGa), tertiarybutylarsine (TBAs), and tertiarybutylphosphine (TBP) as precursors for indium, gallium, arsenic, and phosphorus, respectively. The measurements were performed for two lattice matched $InP/In_{0.47}Ga_{0.53}As/InP$ structures with 100/100/

100 nm (sample A) and 100/5/100 nm (sample B) layers grown on the semi-insulating substrate.

The photoluminescence (PL) spectra from the samples as a function of the optical pumping power were measured at selected temperatures ranging from 50 K to 300 K. The optical pumping was performed using two lasers at different wavelengths, one exciting only the InGaAs well region and the other both the well and the barriers. The long wavelength laser exciting the well region was an infrared solid state laser emitting at $\lambda_E = 1064$ nm (IR laser, beam diameter $\phi = 1.28$ mm), with a maximum output power of 1.6 W, and the short wavelength laser was a frequency doubled Nd:YVO$_4$ laser emitting at $\lambda_E = 532$ nm (green laser, beam diameter $\phi = 2.25$ mm) with a maximum output power of 5 W. Both lasers were passed through a mechanical chopper and focused on areas of 28×10^3 and 2.3×10^3 μm^2 on the sample, enabling excitation densities up to 5.7 and 22 kW/cm^2 for the IR and green lasers, respectively. For the main results, the chopper was set so that the samples were excited by 1.7 ms long pulses and a duty cycle of 8%. The emitted PL was focused on a monochromator and the spectra were measured using an InGaAs photodiode detector with a spectral range of 1200-2600 nm and standard lock-in techniques. During the measurement, the samples were first cooled down to 50 K and the measurements were made at different temperatures without any other adjustments to the measurement setup during the stepping up of the temperature.

Optical power emitted by the sample is proportional to detected power, i.e.,

$$P_{em} \propto \int E \, p(E) \, dE,$$

where $p(E)$ is the measured photon flux, i.e., the detected photocurrent due to PL emitted at photon energy E. The external efficiency η_{opt} of an optically pumped structure can then be estimated as

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$$\eta_{\mathrm{opt}} \propto \frac{P_{\mathrm{em}}}{P_{\mathrm{opt}}} = \frac{\int E\, p(E)\, dE}{P_{\mathrm{opt}}}, \qquad (1)$$

where P_{opt} is the optical excitation power that is assumed to be directly proportional to pump power. The external quantum efficiency (EQE) is estimated similarly as

$$\eta_{\mathrm{qe}} \propto \frac{\int p(E)\, dE}{P_{\mathrm{opt}}}. \qquad (2)$$

Figure 1 shows the peak wavelengths of the PL spectra as a function of excitation power density of sample A at selected temperatures excited with the IR laser. The peak wavelength decreases with increasing excitation power at all temperatures. The blueshift shows that lattice heating is not present even for the highest excitation powers, since lattice heating would decrease the band gap and lead to redshift rather than blueshift.[9]

As a final step to rule out lattice heating, we studied the effect of the pulse width and duty cycle of the excitation, but observed no change in droop when the pulse width and duty cycle were gradually decreased to 0.4 ms and 2%, respectively.

The above considerations show that lattice heating is not significant in the measurements. However, this does not necessarily mean that no carrier heating takes place. In fact, as the excitation power increases, we observe an increase in the full width half maximum (FWHM) of the spectrum as shown in Fig. 2 that shows the FWHM as a function of excitation power for a range of temperatures for IR excitation. The most likely explanations for the broadening are carrier heating or band filling.

Fig. 3(a) shows the quantum efficiency of sample A as a function of detected photocurrent normalized by emitting volume at selected temperatures excited with the IR laser. We used detected photocurrent normalized by the emitting volume as the horizontal axis instead of optical excitation power density because it is expected to be more closely related to the carrier density in the well and allows more

FIG. 2. FWHM as a function of excitation power density of sample A excited with the IR laser at selected temperatures. The observed increase in FWHM suggests that carrier heating or band filling may be present.

direct comparison between different samples and excitation wavelengths particularly in the case of green excitation where absorption takes place also outside the well. The curve at $T = 50$ K is not shown because the peak efficiency is lower than the peak efficiency at $T = 100$ K (the same applies for green excitation). The droop is clearly visible in the figure at all temperatures. There is a relatively large difference in the efficiency between $T = 150$ K and $T = 200$ K. The origin of the difference is currently unknown, but it could be related to the activation of some recombination centers around 200 K. The origin is not considered crucially important since we are mainly interested in the temperature dependence of droop near room temperature. Note that all the quantum efficiencies have been normalized by the maximum quantum efficiency occurring at $T = 100$ K. This enables making direct estimates of the internal quantum efficiency (IQE) of the sample by applying the well known method[10–12] where the maximum IQE at low T is assumed unity and the IQE at other locations is given directly by the normalized
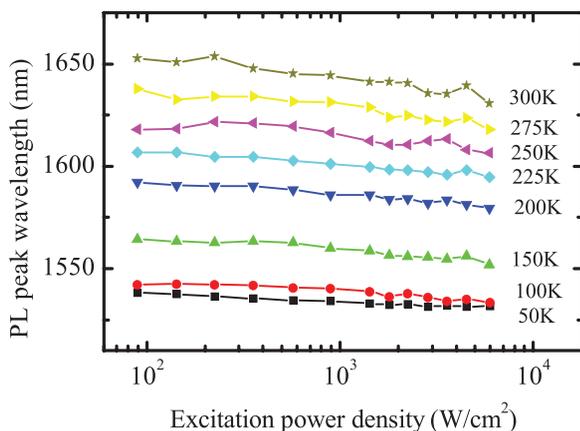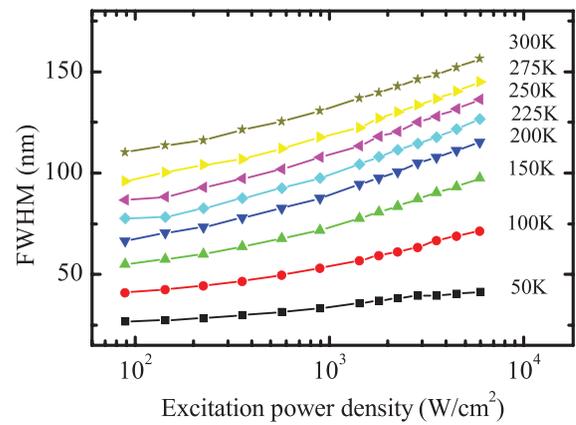
FIG. 1. Peak wavelengths of the PL spectra as a function of excitation power density of sample A at selected temperatures excited with the IR laser. Blueshift with increasing power density suggests that no lattice heating takes place.
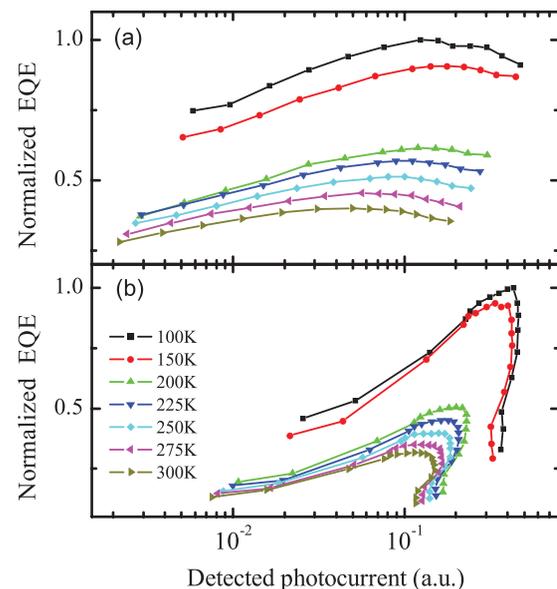
FIG. 3. Quantum efficiency of sample A excited with (a) IR and (b) green laser as a function of normalized photocurrent. The droop is clearly visible in the figure at all temperatures and its onset moves towards higher active region excitations when the temperature decreases.

value. Therefore, the normalized EQE shown in Figs. 3 and 4 in fact corresponds to the approximate IQE. Typically, the low temperature measurements related to measuring IQE are made at around 4 K, whereas our estimates rely on significantly higher temperatures. This is expected to affect the measurement results, but still enable order-of-magnitude estimates of the IQE. At room temperature, this estimate suggests a rather modest 40% IQE for sample A.

Fig. 3(b) shows the quantum efficiency of sample A as a function of normalized photocurrent at selected temperatures excited with the green laser. The green laser provides a larger power density but is not ideal because excitation spreads out to surrounding InP layers and carrier transport and relaxation to the well depends on the temperature. However, when calculating the luminescence, the measured spectrum is integrated over a range of 1300–1850 nm that does not extend to the emission wavelength of InP (<950 nm). The emission from InP therefore does not affect the results. With green excitation, the efficiency curves become significantly narrower and also show a hysteresis at higher excitation powers. This could be related to stronger carrier heating by green excitation. However, the essential features like the existence and the onset position of the droop (defined as the operating point where the EQE starts to decrease) obtained by green excitation are similar to the ones obtained by the IR laser excitation. The room temperature IQE estimate obtained with green excitation is of the same order of magnitude as with IR excitation.

Fig. 4(a) shows the quantum efficiency of sample A as a function of excitation power density excited with the IR laser. Although the temperature dependencies of the detected photocurrent and excitation power at the onset of droop are not strictly the same, essential features of Figs. 3(a) and 4(a) are nearly identical. On a closer inspection the shift in the onset of the droop is slightly smaller in Fig. 4(a) than in Fig. 3(a), but the difference is rather small. Fig. 4(b) shows the

quantum efficiency of sample A as a function of excitation power density excited with the green laser. As in the case of excitation with the IR laser, the essential features related to the onset of droop of Figs. 3(b) and 4(b) are similar.

Fig. 5 shows the quantum efficiency curves of sample B as a function of normalized photocurrent at selected temperatures excited with the green laser. Droop is also clearly visible in the 5 nm quantum well and its onset moves towards higher emissions as the temperature decreases. Results for sample B are only shown for green excitation because the IR laser was not powerful enough to excite the sample to the point where the droop starts. This is most likely due to reduced absorption in the thin active layer. The curves do not have the same sharp, narrow spectrum shape as the ones obtained from sample A with green laser excitation but have a rather flat top. However, as discussed in the context of Figs. 3(a) and 3(b), we expect that the qualitative behavior of droop remains the same independent of the excitation wavelength.

Fig. 6 summarizes how the detected photocurrent at the onset of the droop varies as a function of temperature in samples A and B. The excitation power corresponding to the onset of the droop (not shown) has a slightly weaker, but similar temperature dependence. For all the samples, the droop onset decreases with increasing temperature near room temperature. The recombination of carriers in the samples is governed by

$$-\frac{dn}{dt} = an + bn^2 + cn^3, \qquad (3)$$

where n is the carrier density, a is the Shockley-Read-Hall (SRH) non-radiative recombination coefficient, b is the radiative recombination coefficient, and c is the Auger recombination coefficient. From the statistics of the recombination processes, it follows that the temperature dependence of the a, b, and c coefficients is such that when the temperature increases, the onset of the droop moves towards lower n and output power.[13,14] In the recombination model in Eq. (3), the droop thus originates mainly from the Auger recombination and has a temperature dependence similar to the dependence seen in Fig. 6.
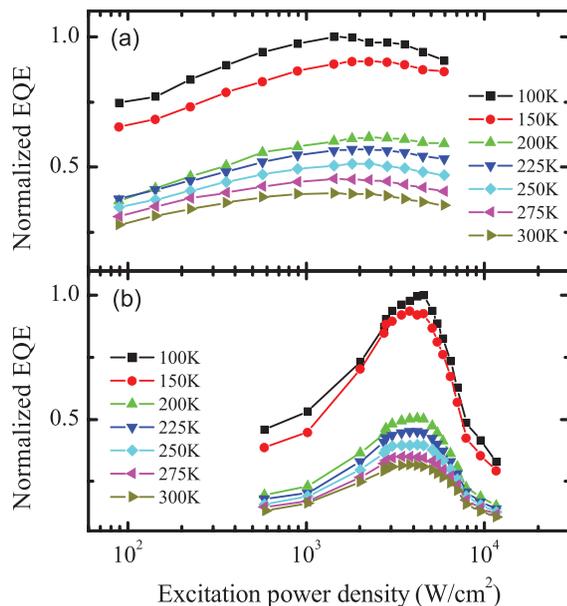

FIG. 4. Quantum efficiency of sample A excited with (a) IR and (b) green laser as a function of excitation power density. The droop is clearly visible in the figure at all temperatures.
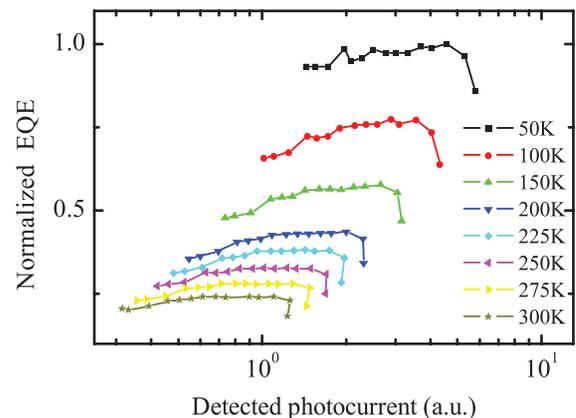

FIG. 5. Quantum efficiency of sample B as a function of normalized photocurrent at selected temperatures excited with the green laser. The onset of droop moves towards higher active region excitations as the temperature decreases.
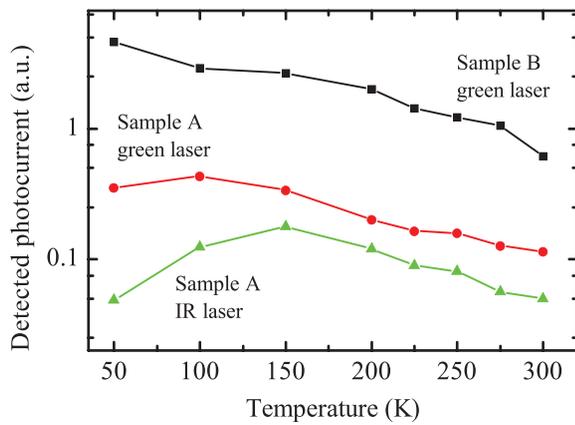
FIG. 6. Normalized photocurrent corresponding to the onset of droop at different temperatures.

To relate our results to the droop in typical III-N quantum well structures[15] where the order of magnitude for the onset of droop for a few nm thick quantum well is typically $J \sim 10$ A/cm^2, the optical excitation density corresponding to the onset of droop in our setup needs to be converted into an easily comparable form. In our measurements, the IR optical excitation power P_{opt} where the droop begun was approximately 400 mW focused on an area $A = 28 \times 10^3$ μm^2 for sample A. The carrier generation rate G per unit volume for optical pumping in sample A and in a typical electrically injected quantum well structure can be compared as

$$G = \frac{\alpha P_{\text{opt}}}{A E} = \frac{J}{q d},$$

where the absorption coefficient $\alpha \approx 2 \times 10^6$ m^{-1},[16] energy of the exciting IR photons is $E = 1.2$ eV, and d is the thickness of the quantum well. Solving J shows that the generation rate at which the droop begins in sample A would correspond to a current density of $J = 7.1$ A/cm^2 in an electrically injected quantum well structure with a thickness $d = 3$ nm. A similar direct comparison for measurements made using the green excitation cannot be made, but since the onset of droop in samples A and B takes place approximately within an order of magnitude in terms of detected photocurrent density, we can indirectly conclude that also the current density corresponding to the onset of droop has to be within the same range as sample A.

In conclusion, we have shown that even extremely simple InGaAs/InP structures exhibit efficiency droop under optical excitation. The temperature dependence of the droop indicates that Auger recombination cannot be ruled out as a possible mechanism for droop as suggested by recent measurements on current injected MQW AlGaInP/GaAs structures. These differences between optical pumping and electrical injection also provide further evidence that in current injected MQW structures, the challenges in efficiently

spreading the current between separate wells strongly enhances and modifies droop, but is not the fundamental reason for it. We have also compared our results with the droop in III-Ns and found that, quite remarkably, the droop in our setup starts at roughly the same excitation density as in typical III-N structures.

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