Thermal quenching of the photoluminescence of InGaAs/GaAs and InGaAs/AlGaAs strained-layer quantum wells

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Photoluminescence in InGaAs/GaAs strained-layer quantum wells is strongly quenched by temperatures above 10–100 K, depending on the well width. Analysis of this dependence shows that the quenching mechanism is thermal activation of electron-hole pairs from the wells into the GaAs barriers, followed by nonradiative recombination through a loss mechanism in bulk GaAs. The addition of Al to the barriers to improve confinement eliminates loss through this route but introduces another loss mechanism, characterized by an activation energy independent of well width and with a smaller pre-exponential factor.

Strained-layer quantum wells of GaInAs grown epitaxially on GaAs have attracted much attention recently, because of their promise for novel device applications (see, for example, Ref. 1). Several authors have reported that the photoluminescence (PL) of these wells is strongly temperature-dependent, being quenched at temperatures upwards of 10 or 100 K, depending on well width.4 This clearly has significant implications for room-temperature operation of optoelectronic devices. In this letter, we report a study of the dependence of PL intensity on temperature and on well width. In multiple quantum well samples an Arrhenius behavior5 is observed, with different activation energies for each well which are close to the differences between the GaAs band gap and the energies of the E1–HH1 transitions between the confined states in the wells. We conclude that carrier loss takes place only through the mechanism of thermal excitation of electron-hole pairs over the heterojunctions into the GaAs barriers and cladding, followed by nonradiative recombination in the GaAs.

For this mechanism, the carrier loss will be reduced or eliminated by increasing the activation energies, and this could be achieved by adding Al to the barriers, or by increasing the indium concentration in the wells. The latter is limited by the amount of strain which can be incorporated, and so we have studied InGaAs strained wells between AlGaAs barriers. In these structures, we find that another loss mechanism is introduced so that the full benefit of the extra confinement is not obtained. This new loss mechanism has not yet been identified.

The samples were grown by molecular beam epitaxy. The results reported here were obtained from an InGaAs/GaAs sample grown with four wells of strained In0.17Ga0.83As of different widths (ME501) between 500 Å GaAs barriers, and an InGaAs/AlGaAs sample with three wells of strained In0.17Ga0.83As of different widths and 300 Å barriers of Al0.25Ga0.75As (ME578). Table I gives details of the structures. The wells are below the critical thickness for strained-layer growth at this composition. The low-temperature PL spectra are shown in Fig. 1. The InGaAs/GaAs sample gives four sharp lines, and the InGaAs/AlGaAs sample, three, of roughly equal intensity at energies corresponding to the E1HH1 transition energies calculated from envelope-function theory for the wells.

In the InGaAs/GaAs sample, the four quantum well emissions are all quenched differently when the temperature is raised, with the higher energy lines quenching at the lower temperatures. At higher temperatures, all the wells show a straight line behavior on an Arrhenius plot of log(PL) against inverse temperature,6 where PL is the luminescence intensity. This behavior corresponds to a thermally activated nonradiative recombination mechanism, and the slopes of the straight portions of the curves give the activation energies for each well. The energies differ significantly among the wells, and in fact we observe that the sum of the low-temperature photoluminescence energy EPL and the activation energy E A for each well is constant, to within 10 or 20 meV, and approximates to the low-temperature band-gap energy of GaAs, 1.51 eV (Table I).

This observation suggests the model shown in Fig. 3, in which the excitation creates electron-hole pairs in the GaAs, trapping and thermal detrapping control the populations in the wells which give rise to the observed PL, and temperature-independent nonradiative recombination occurs in the GaAs. The model can easily be solved by a rate-equation approach, in which the populations of the two levels in

<table>
<thead>
<tr>
<th>Sample</th>
<th>r (Å)</th>
<th>EPL (eV)</th>
<th>E A (meV)</th>
<th>E PL + E A (eV)</th>
<th>U/R</th>
<th>P</th>
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<tr>
<td>ME 501</td>
<td>30</td>
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<td>0.25</td>
</tr>
</tbody>
</table>

*Only the ratios of U, R, and R^* are important. We have taken R = 1, U = R^*, throughout.

steady state are determined by
\[
\frac{dn}{dt} = P - (U + R')n + U \exp(-E_A/kT)m = 0
\]
\[
\frac{dm}{dt} = Un - \left[ U \exp(-E_A/kT) + R \right]m = 0
\]
(1)
giving
\[
I = Rm = \left[ 1 + \exp(-E_A/kT)R'/R + R'/U \right]^{-1}
\]
(2)

The quantities \( n, m, P, U, R, \) and \( R' \) are defined in Fig. 3. Using Eq. (2), the fits to the data for the InGaAs/GaAs sample are shown in Figs. 2(a) and 2(b). Good agreement is found at high temperature, determining the activation energies, and also the form of the curve around the elbow fits the data when we take \( U = R' \). The activation energies \( E \) for the best fits and the values for \( P, U, R, \) and \( R' \) which were used are given in Table I. Note that Eq. (2) is essentially the same as the function which Devine\(^7\) fitted to his data.

This model produces reasonable fits which give activation energies which are uniquely determined within experimental error. The other parameters, \( P, U, R, \) and \( R' \) are not determined uniquely and, therefore, cannot be interpreted rigorously in terms of diffusion and capture. Other sample designs, including barriers to control diffusion, would be more appropriate for such a study. Here, we are concerned only with the activation energies. It should, however, be noted that, depending on its exact mechanism, the rate \( U \) should contain temperature-dependent terms, and these will affect the fitted activation energies slightly. Consequently, we attach no significance to the tendency for the InGaAs/GaAs values of \( E_{\text{pl}} + E_A \) in Table I to be consistently above the GaAs band-gap energy by 10–20 meV.

Returning to the thermally activated loss process of detrapping over the barriers, we might expect to eliminate the effect by increasing the barrier height. Thus, adding aluminum to the barriers might be expected to increase the activation energies. However, we find that the sample with AlGaAs barriers, ME578, shows in fact a very different behavior. Instead of an activation energy depending on the PL energy of each well, the three wells in this sample all have the same value, within error, of 120 meV [see Fig. 2(c) and Table I]. The quenching curves are again reasonably well fitted by Eq. (2), but the relative values for the rates \( U \) and \( R' \) are completely different from those in the InGaAs/GaAs sample (Table I). The result is that although the activation energy is within the spread of values of the activation energies of the InGaAs/GaAs wells, quenching does not start until much higher temperatures, and the reduction in PL intensity at 300 K is much smaller.

For device applications of InGaAs strained-layer quantum wells, it is obviously essential to keep the carriers in the wells at ambient temperature. The quenching of the PL at lower temperatures shows that this is not achieved with...
In$_x$Ga$_{1-x}$As/GaAs with indium concentrations in the $x = 0.2$ range. However, the fact that the only loss mechanism is thermal activation over the barriers is in fact very promising. From Eq. (2), increasing the confinement energy to about 400 meV should be sufficient to prevent significant carrier loss at 300 K during the time scale of luminescence (nanoseconds).

It is noteworthy that the activation energy is the total difference between the transition energy and the GaAs barrier band gap, which means that one does not have to consider separately loss of electrons and of holes. That is, the thermal emission of the electron-hole pair is the rate limiting step. The activation energies which would be expected if emission of either carrier alone were the rate limiting step would be given by the band offsets in the conduction or valence band. These, for a 60:40 band-offset ratio, would both be much less than the observed activation energies, and much lower temperatures would be sufficient for quenching.

If the same mechanism, thermal emission of electron-hole pairs from the wells, had constituted the dominant loss from the InGaAs/AlGaAs quantum wells, the predicted activation energies would have been around 350 meV, and significant quenching would not have occurred until about 250 K [see Fig. 2(c), broken curve]. This sort of structure, with appropriate doping, would form the basis of a strained-layer laser. It is unfortunate that the addition of the Al has introduced another nonradiative mechanism which quenches the PL at temperatures as low as 100 K. Until this mechanism is identified, it will be unclear whether it can be eliminated by changes in sample design or in growth conditions. It may be related to the luminescence fatigue observed by Kirby et al.\textsuperscript{5} in InGaAs/AlGaAs structures at 2 K, and attributed by them to point defects in the AlGaAs due to the low growth temperature used for structures containing indium. However, other authors have reported temperature quenching of the photoluminescence of bulk AlGaAs epilayers grown under conditions nearer to the optimum for AlGaAs; for example, Toyoda et al.\textsuperscript{6} found that the PL in Al$_{0.28}$Ga$_{0.72}$As is quenched from about 40 K with an activation energy of 32 meV. Allowing for the difference in Al concentration, this may be the same mechanism as we observe. Clearly, further work is required to establish whether the loss mechanism can be eliminated so that the full benefit of larger confinement energies can be obtained.

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4 S. Arrhenius, Z. Phys. Chem. 4, 226 (1889).