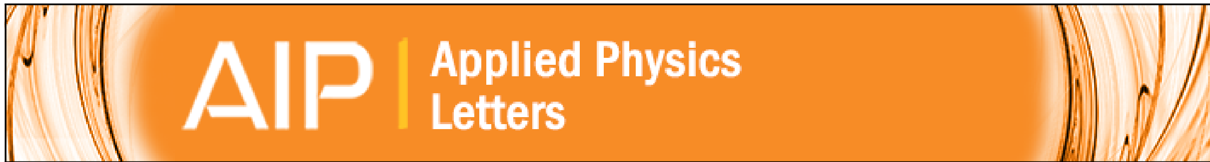

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Citation: Applied Physics Letters **74**, 2540 (1999); doi: 10.1063/1.123891
View online: http://dx.doi.org/10.1063/1.123891
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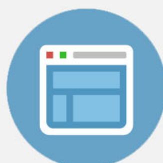
Create a profile.  Sign up today!

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Direct monitoring of thermally activated leakage current in AlGaInP laser diodes

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(Received 1 December 1998; accepted for publication 1 March 1999)

Using specially prepared structures, we have observed emission from a layer of direct-gap ''monitor'' material placed between the *p*-contact layer and *p*-cladding layer of a conventional 670 nm GaInP laser diode at room temperature. This observation provides direct evidence for electron leakage through the *p*-cladding layer in these devices. Furthermore, although emission from the quantum well and waveguide core both pin above threshold, indicating that the Fermi levels clamp throughout the active region, the monitor emission continues to rise above threshold. This is characteristic of a drift component to the leakage current, which we have confirmed by a simulation of the carrier transport processes through the cladding layer with and without drift. © *1999 American Institute of Physics.* [S0003-6951(99)00417-9]

Red emitting lasers, based on GaInP/AlGaInP, are required for an increasing range of applications such as optical data recording and optical sources in photodynamic therapy (PDT). In these devices, it is well known that the threshold current increases super-linearly with temperature and the external differential quantum efficiency (above threshold) decreases with increasing temperature. This behavior is supposed to be due primarily to thermally activated leakage of electrons from the active region through the *X*-band of the *p*-cladding layer.[1,2] This conclusion derives from detailed analysis of experimental measurements of light-current characteristics as a function of temperature,[3] and while comparison with computer simulation suggests that carrier drift makes a significant contribution to the leakage current, measurements of the total current are not able to provide direct evidence for this. Indeed, such measurements do not provide direct evidence for the leakage current itself, whatever its mechanism. In this letter we describe experiments which provide direct evidence for electron leakage and the role of drift currents. We have prepared laser structures with a direct-gap collector region between the *p*-cladding layer and the *p*-contact layer as illustrated in Fig. 1. These structures were processed into oxide isolated stripe lasers with a narrow window in the top contact to enable spontaneous emission to be observed under device-operating conditions[4] from all regions of the structure. Any minority-carrier electrons leaking through the *p*-cladding layer are collected in this ''monitor layer'' where they recombine with holes to produce emission at a wavelength which is characteristic of this layer, and therefore distinguishable from recombination radiation from other parts of the structure. By this means we have monitored the leakage directly and have identified a contribution due to drift. A rate-equation simulation of the experiment has confirmed this interpretation.

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The devices were typical visible-emitting lasers with the additional monitor structure inserted into the *p*-cladding and grown by metalorganic chemical vapor deposition. They comprised a 68 Å wide, compressively strained, $Ga_{0.41}In_{0.59}P$ quantum well set in a region of $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ barrier, together forming the 2000 Å wide waveguide core. This was clad by 1-μm-thick layers of $(Al_{0.7}Ga_{0.3})_{0.51}In_{0.49}P$ doped $9\times10^{17}\,cm^{-3}$ *n*-type and $5\times10^{17}\,cm^{-3}$ *p*-type, respectively. The monitor region consisted of a 5000 Å $(Al_{0.45}Ga_{0.55})_{0.51}In_{0.49}P$ direct-gap recombination layer and a 2000 Å $(Al_{0.7}Ga_{0.3})_{0.51}In_{0.49}P$ barrier, to ensure carriers thermalize within the recombination layer, both doped to $5\times10\,cm^{17}$ using zinc and inserted between the *p*-cladding layer and the *p*-GaAs contact layer. The energy band diagram drawn in Fig. 1, based on self-consistent simulations,[5] shows the three optically active regions of the device: the quantum well itself emitting in the region of 670 nm, the barrier/waveguide core emitting at 595 nm, and the monitor region emitting near 565 nm. These can be spectrally resolved. We compared the light–current and current–voltage

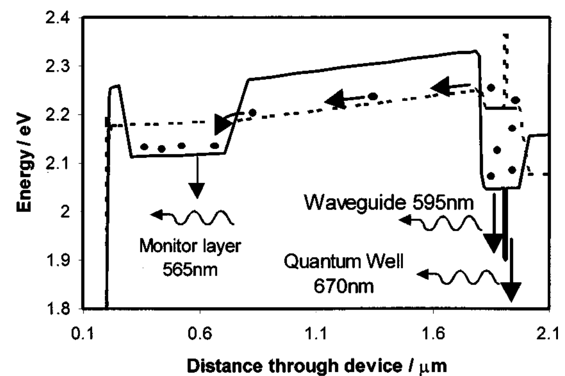

FIG. 1. Calculated conduction band cross section through the *p*-cladding and core region of a typical monitor pit laser at threshold. The solid line represents the direct band gap while the dotted line shows the indirect band gap.

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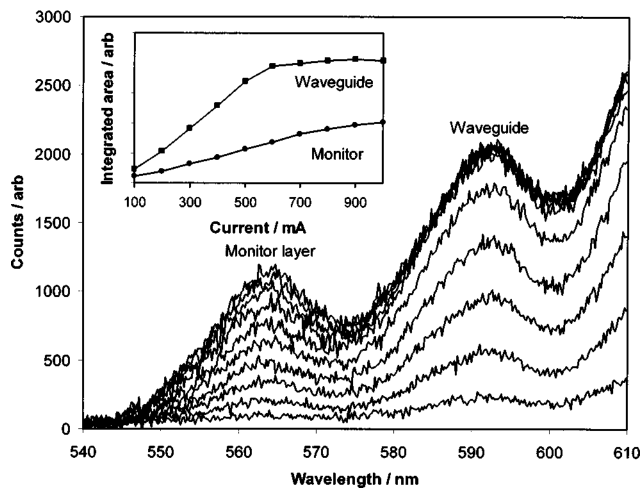

FIG. 2. Spontaneous emission measured as a function of drive current for an energy range corresponding to emission from the waveguide core region and monitor pit. The insert is the integrated area as a function of current for the region corresponding to the monitor pit (circles), and the region corresponding to the waveguide (squares).

characteristics, and the temperature dependence of threshold current between 200 and 380 K, of four monitor devices and four reference devices, identical but for the monitor region, and found these characteristics to be unchanged by the presence of the monitor region.

The spontaneous emission was measured through a window in the *p*-contact metalization as described previously[4] under pulsed conditions. Spontaneous emission spectra from a 600-μm-long monitor laser were measured at room temperature as a function of current. The emission in the region of 670 nm, characteristic of the well, saturated at and above a current of 500 mA which corresponds to the threshold current. We conclude that the Fermi levels at the well clamp at threshold and above.[3] Spontaneous emission spectra from the waveguide core and monitor region is shown for various currents in Fig. 2. The emission at 594 nm, originating from the waveguide core, also clamps above threshold. This contrasts with our previous observations on double-well lasers[3] where simulations have shown that the potential profile continues to change above threshold due to carrier transport between the wells.[6] The results in Fig. 2 show that in the single-well samples used here the Fermi levels are clamped above threshold in the barrier/waveguide region.

The spectra in Fig. 2 show that emission was observed from the monitor region (at 564 nm) and we argue that the only origin of this emission is a flow of electrons from the active region through the *p*-cladding layer to the monitor layer where they recombine with majority carrier holes. The monitor region has the widest direct gap in the complete structure and therefore it is not possible for this material to be optically pumped by radiation produced elsewhere in the device. Integrated areas under the spontaneous emission spectra from the waveguide and monitor region (in equivalent arbitrary units) are shown in the inset of Fig. 2. We interpret these observations as indicating that up to threshold the electron leakage current increases with current as the quasi-Fermi energy for electrons increases. At and above threshold the Fermi levels in the waveguide become fixed and, if there was no significant electric field across the *p*-cladding layer, electron leakage would be due to diffusion alone and this would also clamp at threshold. We interpret the increase in monitor region emission above threshold as evidence for a drift contribution to the leakage: as the majority carrier current through the *p*-cladding increases above threshold, the electric field increases and the rate of extraction of electrons from the active region increases, even though the density of electrons above the potential barrier of the cladding layer, able to flow through this layer, remains constant when the Fermi level clamps. The behavior of the monitor emission shows that the Fermi levels outside the active region do not clamp above threshold, and this is consistent with our interpretation of the behavior of the differential quantum efficiency in lasers of this type.[3]

These observations provide direct evidence for carrier leakage by electron flow in GaInP devices (leakage of minority holes through the *n*-cladding layer would not produce emission from the monitor region as it is located in these experiments) and for the presence of a contribution to this leakage due to carrier drift. We have confirmed this interpretation by computer simulation of the electron flow through the *p*-cladding layer by a finite difference method. The energy levels within the 68 Å quantum well were calculated using the transfer matrix method and all confined electron and hole energy levels were included in the calculation of the quasi-Fermi level positions in the well. The temperature and carrier density dependent gain was obtained from separate gain-current calculations which are consistent with experimental data for temperature dependence of threshold current.[5] The thermionic emission lifetime from the quantum well was calculated using standard thermionic emission theory.[7] We assumed that the density of electrons, able to leak through the cladding layer, was given by the density of electrons above the energy of the *X*-conduction band minima at the interface between the waveguide core and cladding layers. This defined the carrier density in the first element in the finite-difference calculation of carrier transport through the *X*-band of the cladding layer, with each element including equations describing drift, diffusion and nonradiative recombination (specified by an appropriate carrier lifetime). The time constant for capture of carriers from the *X*-band into the Γ-band in the monitor region was set to 1 ps. The field across the *p*-cladding was calculated from the majority carrier current and conductivity. Electron and hole mobilities of 160 and 10 $cm^2 V^{-1} s^{-1}$, respectively, were used. The nonradiative lifetime of electrons in the *p*-cladding layer was chosen to be short, 0.25 ns, due to the high aluminum content.[8,9]

Figure 3 shows the simulated light emission from the waveguide and monitor regions (continuous lines) compared with experimental data (solid points) as functions of current, normalized to the threshold current. The form of these curves below threshold depends critically upon the values used for extrinsic nonradiative lifetimes in the well and waveguide regions and we have made no serious attempts to match simulation and experiment over this part of the curves. Indeed, since experiments show that the carrier densities in well and waveguide core both pin above threshold, these parameters do not affect the form of the behavior of monitor emission simulated above threshold, which is our chief con-

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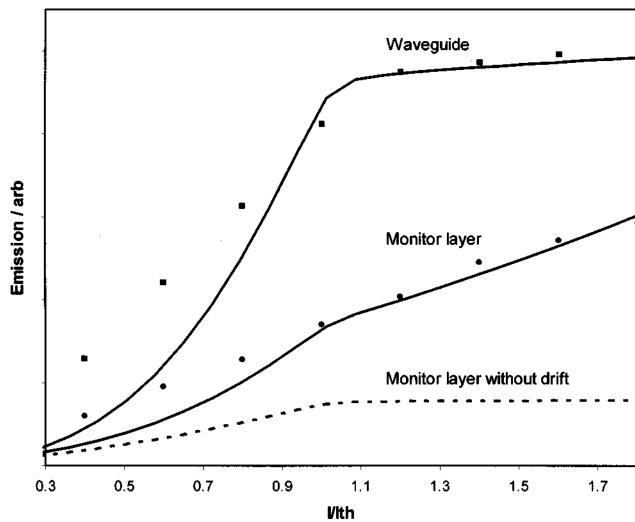

FIG. 3. Comparison between the integrated area as a function of threshold current for the monitor layer and waveguide (points), with simulated carrier density data calculated at room temperature using 450 μm long, 50 μm wide devices, with a calculated threshold of ~277 mA, (lines). The dashed line indicates the effect of turning off drift in the simulation, on the monitor layer emission.

cern. By virtue of the nature of the model, the emission from the waveguide stops increasing above threshold, as observed in the experiment, whereas the simulated recombination from the monitor region continues to increase, in agreement with experimental data. When we remove the drift component from the carrier transport model for the *p*-cladding, the monitor emission also clamps above threshold (shown by the dash line in Fig. 3). This is distinctly different from the observed behavior and confirms our conclusion that our experimental observations provide direct evidence for the contribution of drift to the leakage process, and hence its importance in determining the differential quantum efficiency above threshold.

In summary, by means of a top-contact window we have observed emission from a direct-gap monitor region placed between the *p*-contact and *p*-cladding layer of a conventional 670 nm GaInP laser diode. This observation provides direct evidence for electron leakage through the *p*-cladding layer in these devices. Furthermore, although the emission from the quantum well and waveguide core both pin above threshold, indicating that the Fermi levels clamp throughout the active region, the monitor emission continues to rise above threshold. This indicates the presence of a drift component to the leakage current, a conclusion we have confirmed by a simulation of the carrier transport processes through the cladding layer.

The authors thank the Engineering and Physical Sciences Research Council for their support of this work through funding for PMS and a studentship for SAW. They also thank Graham Berry and Huw Summers for valuable discussions.

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