Direct Measurement of the Carrier Leakage Out of the Active Region in InGaAsP/InP Laser Heterostructures

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Abstract— **Leakage of electrons out of the active region of InGaAsP/InP laser heterostructures at different temperatures was measured by a purely electrical method. Comparison of the obtained results with the results of modeling indicates that special attention should be paid to the acceptor doping levels in the p cladding layer immediately adjacent the active region. Lower acceptor concentration may lead to unacceptably high thermionic leakage.**

I. INTRODUCTION

THERMIONIC emission of carriers out of the active region of a semiconductor laser limits the fraction of injected carriers that recombine in the active region. The dependence of the thermionic leakage current I_L on the injection current I_{inj} is an important factor characterizing the laser performance. Thermionic emission depends on the energy barriers confining electrons in the active layer, which, in turn, depend on the hole transport across the heterostructure [1].

Theoretical evaluation of the dependence $I_L(I_{inj})$ is a complicated problem [1]–[3]. For a given I_{inj} the shape of the barrier confining electrons is determined by the transport of holes in the forward direction and hence it depends on the valence-band discontinuity and the doping in the depleted region of the cladding layer adjacent to the active layer. Moreover, in the operating regime of a laser diode the distance over which the barrier potential energy in the vicinity of the active layer varies by kT is typically longer than the mean free path of holes in the depleted region, so that the diffusion rather than the thermionic theory of barrier injection is often more closely applicable. This means that the hole mobility is also a factor in determining the barrier height confining electrons. For a given confining barrier the value of I_L depends on the concentration and temperature of electrons in the active layer.

Experimental studies of $I_L(I_{inj})$ are important for understanding the sources of non-linearity in analog lasers. Moreover, they can be expected to improve our understanding of the temperature dependence of threshold current and thus lead to a better design of lasers for high-power applications.

Carrier leakage over the heterojunction barrier in 1.3-μm wavelength GaInAsP/InP light-emitting devices was first observed by measuring the radiative recombination in a specially designed surface-emitting LED structure [4] and was later measured electrically, using a unique laser/transistor structure [5]. High-energy light emission caused by the carrier leakage into the wider-bandgap confinement layers has been observed by several groups [6], [7]. Thermionic emission from the active layer was investigated [8] by inference from the combined measurements of the external quantum efficiency and the internal loss.

In this work, we propose and demonstrate a new design for purely electrical direct measurements of I_L and its dependence on I_{inj} in laser heterostructures at different temperatures. Unlike the previously reported structure [5], our design allows to measure the thermionic emission of carriers out of the active region without affecting the laser diode characteristics.

II. EXPERIMENT AND MODELING

Our studies employed the three-terminal heterostructure illustrated in Fig.1. In addition to a conventional InGaAsP/InP laser diode layers, the device contains a small-area collector, whose layer structure is shown in the inset to Fig 1. Fig. 2 displays the energy band diagram in a cross-section of the device under the collector. The diagram corresponds to the operating bias regime and illustrates the idea of the experiment. Electrons, thermionically emitted into the p-cladding layer, diffuse there like minority carriers in a base of a bipolar transistor; inasmuch as the total "base" thickness (W = 1.35 μm) is narrower than the estimated electron diffusion length ($L_D \gtrsim 3$ μm) in the cladding layers, most of the electrons are collected in the positively biased n$^+$ contact. Since the collector area is so small in our structure (1% of the diode area), we can safely assume that the presence of the collector does not affect the laser diode performance.

The lattice-matched InGaAsP/InP heterostructure was grown by MOCVD on a conducting InP substrate and processed into a device using optical lithography and wet etching. First, we evaporated a 2000-Å thick Au layer patterned by lift-off in a small rectangular area (10 × 5 μm) corresponding to the future collector; this metal layer was then used as an etch mask. We etched down about 2000 Å of quaternary (Q) materials, stopping inside the pQ layer. The crucial fabrication step involved the evaporation of a self-aligned metal contact to the pQ layer, which had to provide an ohmic contact to the laser diode without degrading the collector pn junction. The remaining part of the pQ layer, not

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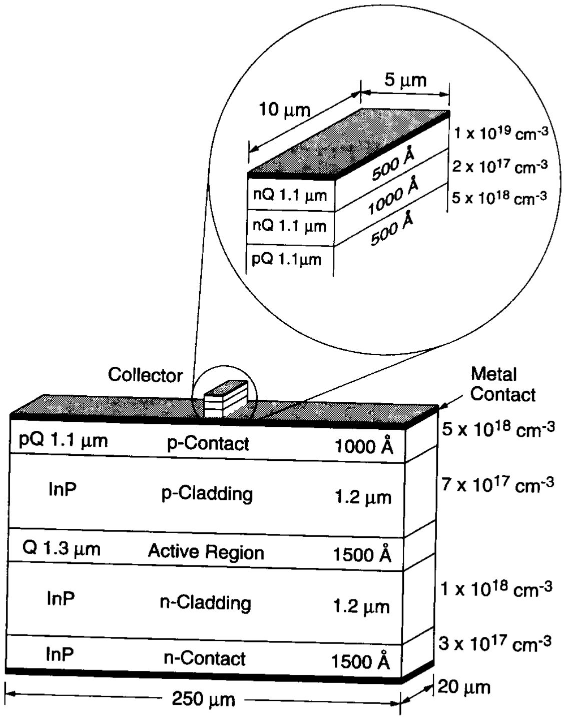

Fig. 1. Schematic cross-section of the device.

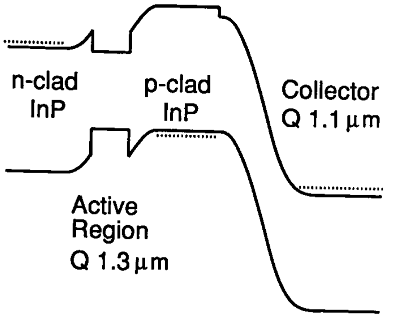

Fig. 2. Structure band diagram under bias.

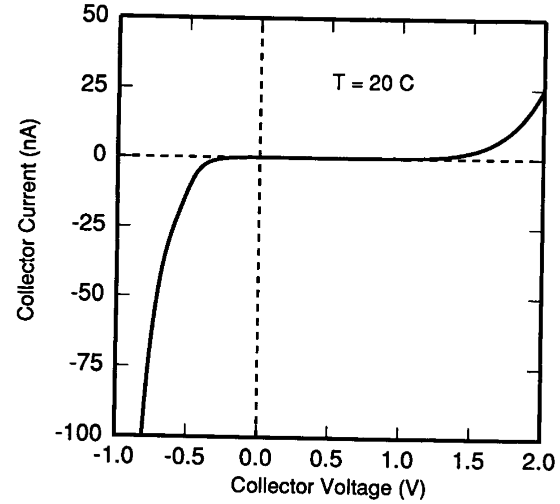

Fig. 3. Current-voltage characteristic of the collector diode at zero injection level in the laser diode.

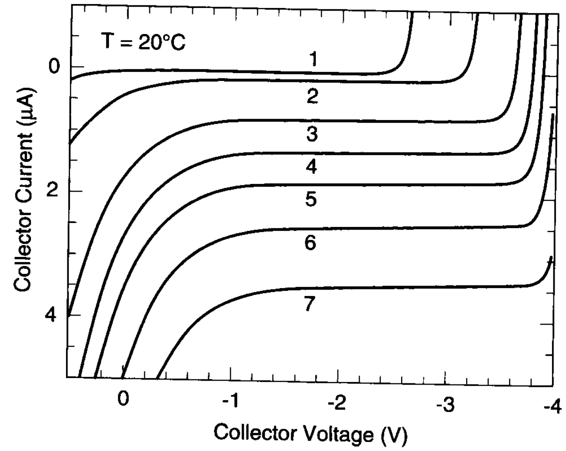

Fig. 4. Dependence of the collector (leakage) current on the collector voltage for several injection currents: 1–6.7 mA, 2–24.8 mA, 3–48.8 mA, 4–60.2 mA, 5–69.6 mA, 6–79.8 mA, 7–91.7 mA.

covered by the contact, was etched away. The metal n contact was evaporated on the backside after the wafer was polished down to a thickness of 100 μm. In the last fabrication step the wafer was blanket-covered with 3000-Å thick SiO_2 layer, windows were opened and final metal (Au, 2000 Å) contact pads were evaporated.

Fig. 3 shows the I-V characteristic of the collector diode, measured at 20°C in the absence of the laser diode injection. The excellent quality of the collector pn junction evident from Fig. 3, is crucial for the success of our experiment. At reverse voltages about 1 V below the onset of a soft junction breakdown, the pn-junction leakage is below 100 pA.

Fig. 4 presents the I-V characteristics of the collector diode measured under different levels of the laser diode injection. As I_{inj} increases, the collector characteristic shifts toward higher collector voltages due to a voltage drop along the p contact layer. At the same time, the reverse bias collector current increases sharply, reaching the value of several μA. It is clear that only electrons thermally excited from the active region can reach the collector contact and consequently the collector currrent is a good measure of the thermionic leakage.

Accuracy of this measure is determined by four possible sources of error, all rather minor in our estimate. First, we could expect trouble from the leakage in the reverse-biased pn junction; fortunately, this has been ascertained to be negligible, Fig. 3. Second, we must be concerned that the collector does not funnel in the minority electrons from areas outside the junction. Here, our self-aligned fabrication procedure has been essential. Electrons, injected in the cladding layers under the metal contact, diffuse in the same fashion as those under the collector; in the vicinity of the contact these electrons are swept into the metal by the electric field of the Schottky barrier. Only those electrons that reach the etched surface in

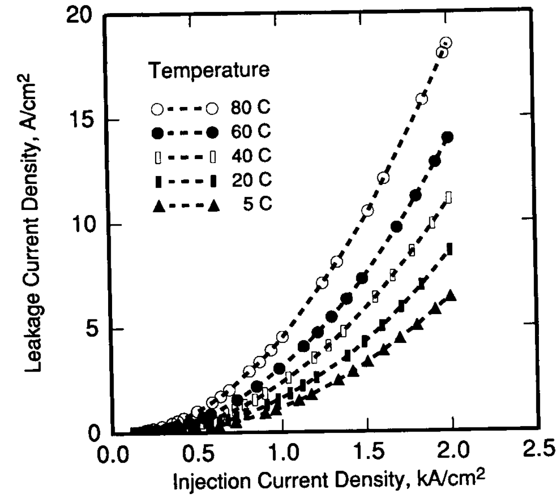

Fig. 5. Dependence of the leakage current density on the injectioncurrent density, measured at different lattice temperatures.

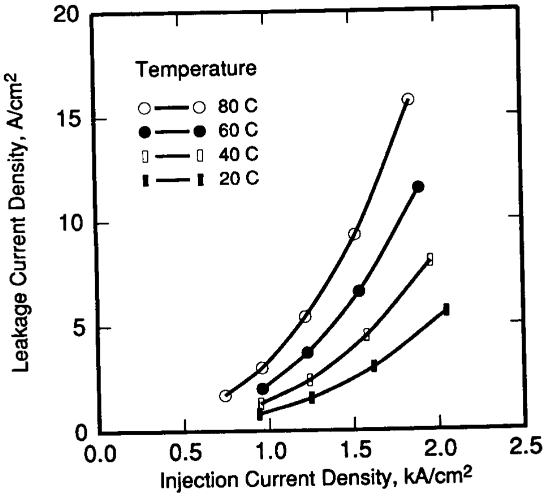

Fig. 6. Dependence of the leakage current density on the injection current density, calculated in the framework of the model [1] for different ambient temperatures.

the gap (at most 1000 Å) between the collector and the self-aligned metal—and do not recombine there—may contribute an extra collector current, and consequently this source of error is quite negligible. Third, our results could be affected by the nonuniformity of the hole flow into the active region due to the presence of the collector, which depends on the spreading resistance in the film under the collector. For the doping used in our experiments, the film conductivity is sufficiently high that the hole flow near the active region can be regarded as perfectly uniform. Finally, a fraction $(1 - \alpha)$ of the injected electrons do not reach the collector but recombine in the p-cladding, which can be regarded as a transistor base with a transport factor $\alpha \approx \cosh^{-1}(W/L_D) \lesssim 0.1$. This appears to be the only tangible source of error; it may result in a slight underestimation of the thermionic leakage current.

Thus, we can express the measured values of the collector current in terms of the *density* of thermionic leakage per unit area of the laser diode. Fig. 5 plots the density of the leakage current against the injection current density at different temperatures. We see that at 80°C and $I_{inj} \approx 2$ kA/cm^2 the leakage reaches almost 1% of the total injection. This value is in agreement with the theoretical prediction [2].

Fig. 6 shows the results of calculations carried out in the framework of the model [1]. In this model, based on the diffusion theory of barrier injection, the barrier height for the injection of holes depends on the acceptor concentration in the p cladding layer and also on the hole mobility. If we take the nominal acceptor concentration (confirmed by SIMS analysis) $N_A = 7 \times 10^{17}$ cm^{-3} and the mobility $\mu_h =$ 40cm^2/V · s, corresponding to undepleted pQ layers, then our calculation substantially underestimates the thermionic leakage (by more than a factor of 5). However, it should be noted that the N_A which matters is that in a depleted sublayer adjacent the active region. Approximate agreement between the experiment and theory can be achieved assuming a lower acceptor concentration in this sublayer. The doping value in the sublayer may be lower than that deep in the cladding layer because in the process of growth the dopant flux has been ramped up from a low value in the active layer. Also the mobility μ_h may be lower in the depleted sublayer, because of the Coulomb scattering by unscreened charged acceptors. The model curves in Fig. 6 have been calculated without adjusting the mobility but assuming, in agreement with the SIMS data, that in the first 500 Å of the cladding layer the acceptor concentration is $N_A = 1.75 \times 10^{17}$ cm^{-3}.

III. DISCUSSION

The results of modeling indicate that increased thermionic leakage may be caused by a lower than nominal doping level in the cladding at the interface with the active layer. At the same time we should be aware that the model [1] may not be sufficient for a quantitative analysis of thermionic leakage because it neglects the possible heating of carriers in the active layer by the power flux associated with the current across the heterojunction barriers [9]. Our present analysis assumes, following [1], that the temperature T_e of the electron-hole plasma in the active layer does not significantly depart from the lattice temperature T. However, it was shown experimentally [10] that T_e can exceed T by more than 50 K even at moderate injection levels.

In conclusion, we have proposed a novel design for a purely electrical measurement of thermionic emission of electrons from the active layer of a double-heterostructure laser. Comparison of the obtained results with the existing models suggests that special attention should be paid to the acceptor doping levels in the p cladding layer immediately adjacent the active region. Unintentionally lower acceptor concentration may lead to unacceptably high thermionic leakage. Further work is required, both theoretical and experimental to obtain a quantitative modeling of the measured leakage.

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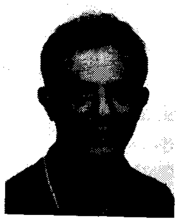

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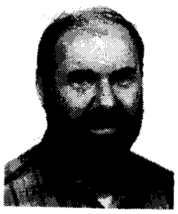
R. F. Kazarinov, photograph and biography not available at time of publication.



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T. Tanbun-Elk, photograph and biography not available at time of publication.

P. A. Garbinski, photograph and biography not available at time of publication.