Direct measurement of the carrier leakage in an InGaAsP/InP laser

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Carrier leakage over the heterobarrier in an InGaAsP/InP laser is measured directly in a laser-bipolar-transistor structure. Experimental results indicate a significant amount of carrier leakage under normal laser operating conditions.

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A continuing problem plaguing light-emitting diodes (LED's) and laser in the quaternary compound of InGaAsP emitting in the spectral range of 1.1–1.5 μm is the severe output power saturation (LED's) and high-temperature sensitivity (lasers). Recently, experiments performed by Yamakoshi *et al.*[1,2] and Wada *et al.*[3] have demonstrated significant carrier leakage over the heterobarrier in 1.3- and 1.5-μm LED's. In the case of lasers there exists indirect experimental evidence indicating the existence of such leakage currents.[4,5] This leakage current may be responsible for the "second break point" in lasers[6] and the output power saturation in LED's. However, the magnitude of the leakage current could only be estimated. We report here on a direct experimental observation and measurement of the leakage current in an InGaAsP/InP laser emitting at 1.2 μm. The measurement employs a novel laser-bipolar-transient-type device. The results show quantitatively the existence of a considerable amount of minority-carrier leakage in the present laser structure and that the leakage tends to increase with the injection current, even beyond the lasing threshold.

A schematic representation of the laser-bipolar transistor used in this work is shown in Fig. 1. The emitter-base junction functions as in an ordinary laser diode. The collector-base junction is reverse biased, as in a bipolar transistor, to collect the leakage current. The laser part of the transistor is similar to that of a terrace mesa InGaAsP/InP double heterostructure (DH) laser.[7,8] However, an extra N^+-InP layer was added in order to collect the leakage current. The composition and the thickness of the four epitaxial layers are N^+-InP collector layer (Sn doped, $N = 2\times 10^{18}$ cm^{-3}, 3–4 μm), P^--InP confining layer (Zn doped, $P = 2\times 10^{17}$ cm^{-3}, 1.5 μm), undoped InGaAsP active layer (background electron concentration is $4–9\times 10^{18}$ cm^{-3}, 0.2 μm), and N^+-InP confining layer (Sn doped, $N = 2\times 10^{18}$ cm^{-3}, 4 μm). The last three layers constitute a typical DH InGaAsP/InP laser. After epitaxial growth, selective etching was performed on the top N^+-InP layer[7,8] with the resulting mesa structure formed as shown in the left part of Fig. 1. In order to obtain low threshold current, the quaternary layer was undercut with a selective etchant to reduce the width. Part of the wafer was also etched down to the bottom N^+-InP layer to facilitate the fabrication of the collector contact as shown in the right part of Fig. 1. Finally, three electrical contacts for the emitter, base, and collector of *N-p-N* bipolar transistor, were fabricated as shown.

Under forward bias condition, the emitter-base junction acts as a laser diode. The electrons are injected from the N^+-InP (emitter) into the quaternary region. In this structure, those electrons which have surmounted the heterobarrier at A and arrived at the base-collector junction (B), will be swept out by the electric field in the reverse-biased junction. As the thickness of the P^--InP layer is smaller than a diffusion length of the electron ($\sim$ 3–4 μm[9]), most of the leaking minority carriers will be collected, thus giving rise to I_c. Since the electron leakage is expected to be much more significant than hole leakage in this system due to the relatively small effective mass of electrons in the active region, the present structure is specially designed to measure the electron leakage. However, by changing the doping of the epitaxial layers properly, the hole leakage can also be examined.

Since the active layer of the laser is bounded on the sides by semi-insulating InP and air, respectively, the current leakage due to carriers bypassing the active region through the burying layer, as is the case in some conventional heterostructure lasers, is completely eliminated. This enables us to measure directly the carrier leakage over the heterobarrier.

The turn-on voltage of the laser junction is about 0.7 V and the reverse breakdown voltage of the collector junction is about 8–9 V. The threshold current of the laser (for an active layer width $\sim$2 μm and a cavity length of 250 μm) ranges from 15–30 mA, the lowest value being 12 mA.

A block diagram depicting the measurement circuit is shown in Fig. 2. The base current (I_b), the reverse-bias voltage of the collector junction (V_c), the leakage current (I_c), and the light output were simultaneously monitored and measured. The emitter current (I_e) is the total injection current to the laser, I_b the recombination current that is mostly in the low band-gap *p*-type active layer, and I_c is the leakage current. The general behavior of the collector current versus the collector voltage is shown in Fig. 3. As the collector voltage increases, the collector current also increases and eventually saturates. This saturation occurs when the junc-

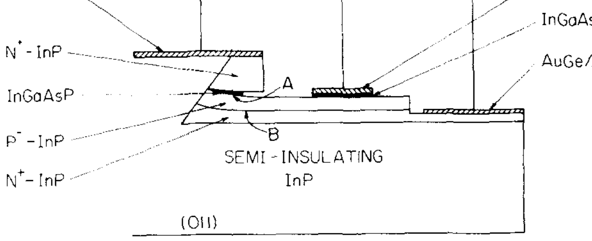

FIG. 1. Schematic representation of the laser-bipolar-transistor structure.

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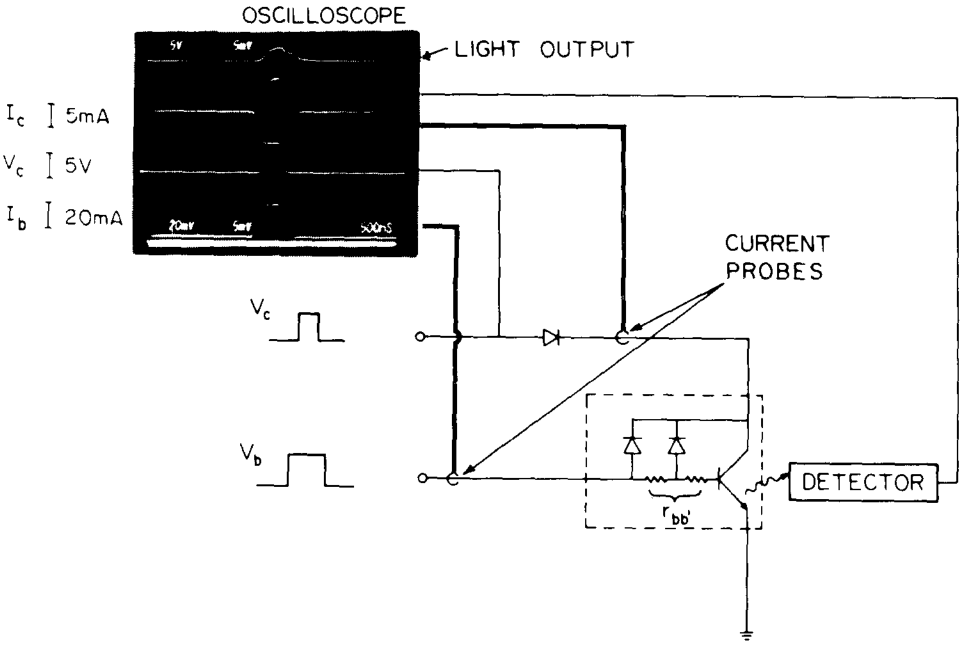

FIG. 2. Block diagram and photograph of the measurement circuit and signal, $r_{bb'}$ is due to the distributed resistance at the base-collector junction.

tion is reverse biased and all the electrons which have overcome the heterobarrier are collected. Hence, this saturated collector current is just the electron leakage current (assuming negligible carrier loss in the P^--InP layer by recombination process or other processes). It has been found that under low injection condition, the electron leakage is very small. However, it increases rapidly with increasing injection. For the present structure, the leakage current is about 15%–30% of the total injection current when the latter is about 20 mA (corresponding to a current density ~ 4 kA/cm^2, which is near the threshold current density of the lasers). A typical leakage current versus the total injection current (I_e) characteristics is shown in Fig. 4. It is noticed that the leakage current increases with injection current and that no saturation occurs even above threshold.

The leakage current was also measured with a transistor curve tracer. The photograph inserted in Fig. 3 shows a typical characteristics of the transistor in the common-emitter configuration. As can be seen from the photograph, the collector current, which corresponds to the leakage current, increases superlinearly with the base current. It should be noted in passing that the present experiment is equivalent to the measurement of β in a transistor. To ensure that the current leakage does not flow through the parasitic junction

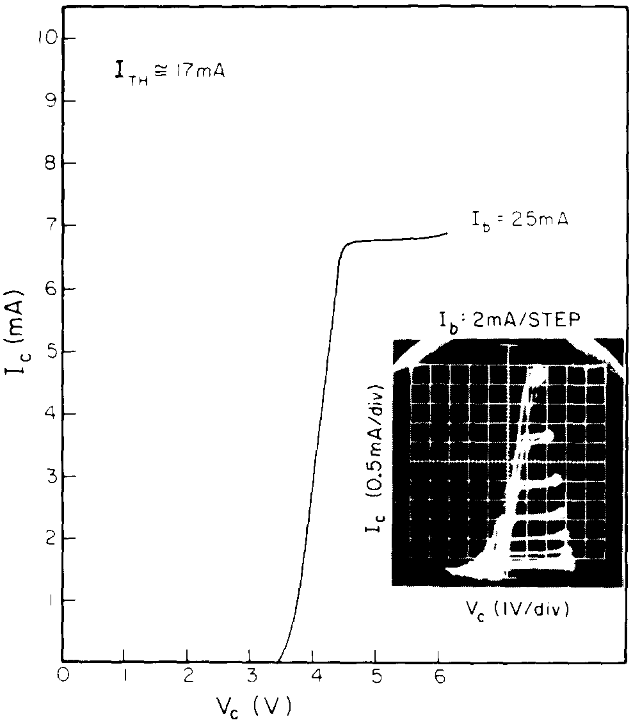

FIG. 3. General behavior of the collector (leakage) current and collector voltage. A transistor type curve trace of the collector current vs collector voltage at several base currents is shown in the inserted photograph.

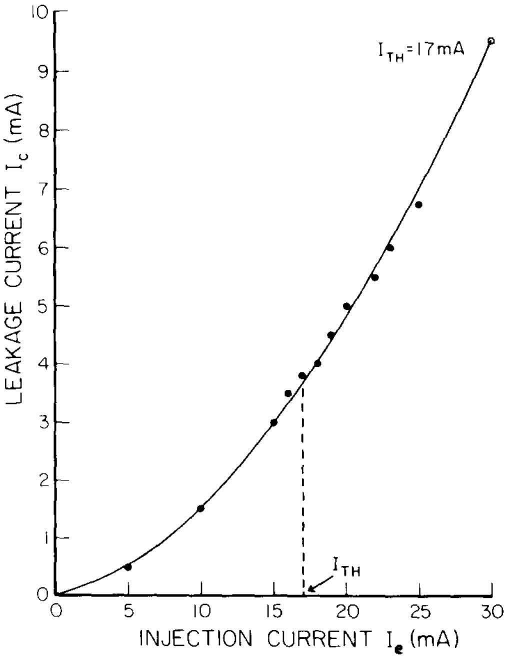

FIG. 4. Typical leakage current vs injection current characteristics.

near the tip of the active layer, the quaternary layer of some of the lasers was etched away completely. The resulting device was then measured as described above. The results indicate negligible current leakage through this parasitic junction.

A most interesting, and at first baffling result of the present work is the continued increase of the leakage current beyond threshold. According to ordinary thermionic emission and diffusion models, the electron leakage current depends on the carrier concentration at the heterobarrier.[9,10] Thus, one would expect that since carrier concentration is virtually clamped above threshold, so would the leakage current. This is in contrast to the present results. It appears that the existing theoretical models are inadequate to account for the behavior of the leakage current. We propose here a model for the leakage current in which the electric field in the P^--InP confining layer is taken into account. Only a brief description will be given here. Details of the model, which includes the field, the band structure at the interface, the boundary conditions at the heterobarrier, and carrier heating[3] and/or Auger enhanced leakage,[11] will be presented in a forthcoming paper.

Under high injection conditions, it can be estimated that there exists a substantial electric field across the confining P^--InP layer. This electric field, which has been neglected so far, enhanced the leakage current and is also responsible for the unclamped behavior above threshold. The current densities above which the leakage current is field rather than diffusion dominated can be estimated approximately. The hole current can be written as

$$J_p = e\mu_p N_A E,$$

where e is the electronic charge, μ_p the hole mobility, N_A the doping level in the P^-InP layer, and E the electric field strength. The ratio of the drift and diffusion components of the leakage current is then given approximately by

$$\frac{J_{\rm drift}}{J_{\rm diff}} \approx \frac{J_p W \mu_n}{e D_n \mu_p N_A},$$

where W is the width of the confining layer, μ_n the electron mobility, and D_n the electron diffusion constant. Taking $\mu_n = 3000\ \mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{sec}^{-1}$, $\mu_p = 150\ \mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{sec}^{-1}$, $W = 1.5$ μm, and $D_n = 77\ \mathrm{cm}^2\ \mathrm{sec}^{-1}$, $N_A = 10^{17}\ \mathrm{cm}^{-3}$ as appropriate in the present case, it is found that the drift current is larger than the diffusion current when the hole current exceeds $\sim 420\ \mathrm{A/cm}^2$. Since normal lasers operate at much higher current densities, the drift component of the leakage current will dominate. The leakage current in this model is also inversely proportional to the doping level in the confining layer. This is consistent with the experimental observation of the dependence of T_0 on P-layer doping level.[12]

In conclusion, the electron leakage over the heterobarrier has been observed and measured directly in an InGaAsP/InP laser. The results indicate that at high current densities, the electron leakage current is a considerable portion of the total injection current. When the current density is about 4 kA/cm^2, the leakage current is about 15%–30% of the total current (for the present structure and some of its variations). No clamping in leakage current has been observed. This leakage current will affect the performance of the laser, such as the increase in the threshold current, the decrease in the external quantum efficiency, the degradation in the linearity of the light-current characteristics, and also the sensitive dependence of the threshold current on ambient temperature.

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