Carrier leakage and temperature dependence of InGaAsP lasers

T. R. Chen, B. Chang, L. C. Chiu, K. L. Yu, S. Margalit, and A. Yariv
California Institute of Technology 128-95, Pasadena, California 91125

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A direct measurement of electron and hole leakage in InGaAsP/InP lasers has been carried out. The effect of electron leakage on the temperature sensitivity of InGaAsP/InP lasers has been revealed.

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InGaAsP lasers emitting in the range of 1.2–1.6 μm have been prime candidates for light sources in optical communication since the emission wavelengths lie in the spectral region where present fibers exhibit low loss and negligible dispersion. However, the threshold currents of quaternary lasers were found to be sensitive to changes in ambient temperature; these lasers are usually characterized by a low T_0 (assuming $I_{\rm TH} \sim e^{T/T_0}$). Many mechanisms have been proposed to account for the observed low T_0. In particular, nonradiative Auger recombination within the active region and electron leakage over the InGaAsP-InP heterobarrier have received much attention. Recent experiments have provided direct evidence for the Auger process[1] and for electron leakage[2] in lasers. In this letter a systematic study of the carrier leakage is presented where hole leakage as well as electron leakage is measured. The direct measurement of electron leakage has been extended to lasers emitting at 1.3 μm. Measurement of the electron leakage as a function of temperature in the range of 10–32 °C has been performed, and a "leakage-free" characteristic temperature T_0' has been deduced. The hole leakage is found to be negligible. A brief discussion and interpretation of the result will be given.

The laser-bipolar-transistor structure used for the measurement of electron leakage over the barrier is identical to those described in Ref. 2. A schematic of the device is shown in Fig. 1(a). The composition and thickness of the four epitaxial layers are n^+-InP collector layer (Sn doped, $n = 2\times10^{18}$ cm^{-3}, 3–4 μm), p-InP confining layer (Zn doped, $p = 2\times10^{17}$ cm^{-3}, 1.5 μm), undoped InGaAsP active layer (background electron concentration is 4–9×10^{16} cm^{-3}, 0.2 μm), and n^+-InP confining layer (Sn doped, $n = 2\times10^{18}$ 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 with the resulting mesa structure formed (with n^+ portion being $\sim 5\,\mu$m wide) as shown in the left part of Fig. 1(a). In order to obtain low threshold current, the quaternary layer was undercut with a selective etchant to reduce the width to 1–2 μm. 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(a). Finally, three electrical contacts for the emitter, base, and collector of the n-p-n bipolar transistor were fabricated as shown.

The structure utilizes the reversely biased base-collector p-n junction to collect the "leaked" electrons. The emitter-base junction under forward bias condition acts as a laser diode. The electrons are injected from the n^+-InP (emitter) into the quaternary region. Those electrons which have surmounted the heterobarrier and arrived at the base-collector junction 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, most of the leaking minority carriers will be collected, thus giving rise to collector current. The leakage current is the saturated collector current measured before breakdown of the reverse-biased collector-base junction. We have measured the electron leakage of lasers emitting at 1.3 μm. At injection current density of ~ 4 kA/cm^2, the electron leakage current is about 10–30% of the total injection current (at room temperature), which falls in the same range as for the 1.2-μm lasers reported in Ref. 2.

Electron leakage current has been measured in the temperature range of 10–32 °C and is found to be highly temperature sensitive. The electron leakage current increases by a factor of 1.4 from 10 to 32 °C, when the total injection current is held at 20 mA (see Fig. 2). Direct measurement of the leakage current is used to probe its effect on the temperature sensitivity of the threshold current. Temperature characteristics of an ideal leakage-free laser can be obtained by subtracting, at each temperature, the leakage current from the measured threshold current. The results for a laser with a

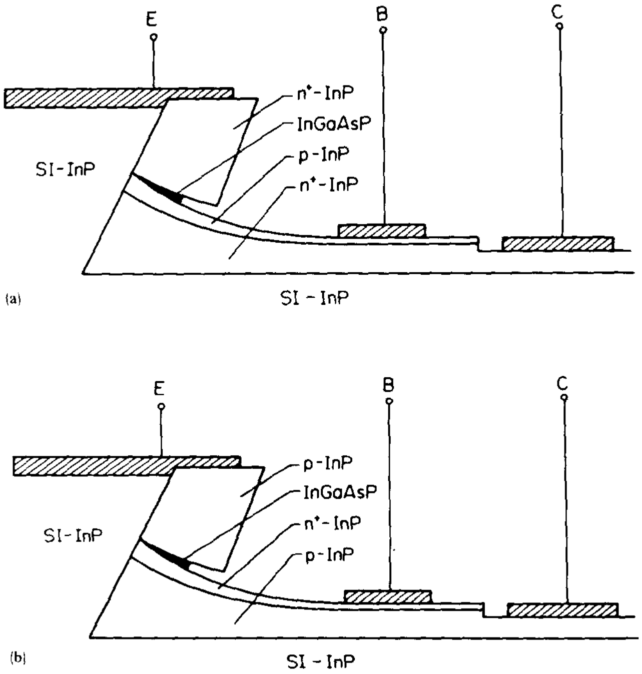

FIG. 1. Laser-transistor structure for direct measurement of (a) electron leakage and (b) hole leakage.

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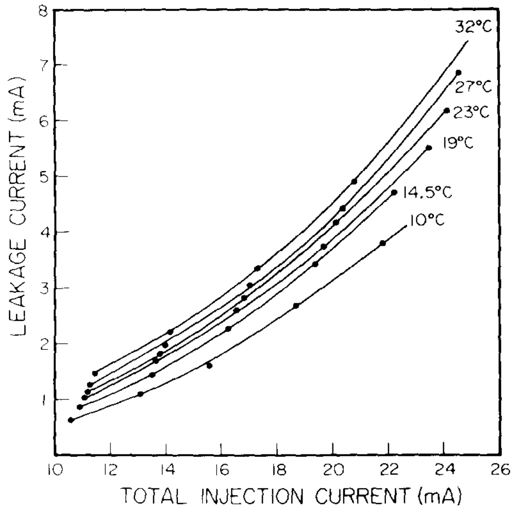

FIG. 2. Electron leakage current as a function of total injection current at different temperatures.

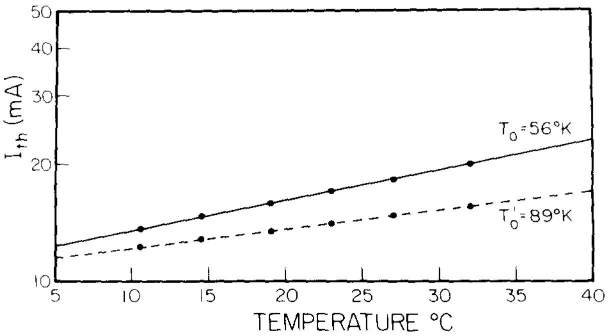

FIG. 3. T_0 of the laser. Solid line shows the conventional temperature characteristics with $T_0 = 56$ °K. Dashed line shows the leakage-free temperature characteristic with $T_0' = 89$ °K.

threshold current of 17 mA (at 23 °C) are presented in Fig. 3. From the threshold current measured at different temperatures, a T_0 of 56 °K is obtained, with the corresponding leakage-free characteristic temperature T_0' equal to 89 °K. This demonstrates for the first time the effect of leakage current on the temperature sensitivity of quaternary lasers.

By changing dopant types on the structure of Fig. 1(a), we have also successfully fabricated a similar device for measuring the hole leakage. A schematic drawing of the structure is shown in Fig. 1(b). The dimensions are similar to Fig. 1(a). The composition and thickness of the four epitaxial layers are p-InP collector (Zn doped, $\sim 4\,\mu$m), n^+-InP base (Sn doped, ~ 0.5–$1\,\mu$m), undoped InGaAsP active layer ($\sim 0.2\,\mu$m), and p-InP emitter (Zn doped, $\sim 4\,\mu$m). In contrast to the electron leakage result, no hole leakage current (to within 1% of the total injection current) was detected at the collector junction—even when the injection current density is over 10 kA/cm^2. We are thus led to the conclusion that hole leakage over the heterobarrier in InGaAsP lasers is negligible. This is, to our knowledge, the first experimental "measurement" of the hole leakage in lasers.

The null result of the experiment is not surprising. According to a model analysis,[3] the dominant contribution to the leakage current is the field enhanced drift component rather than the diffusion component, and the drift component depends crucially on the doping level in the adjacent cladding layer. Since holes have larger effective mass and the ratio of the mobilities (μ_p/μ_n) is about 0.05, the drift component of the hole leakage is expected to be at least 400 times less than that of electron leakage.[3] Furthermore, the cladding layer in this case is heavily N doped, hence no field enhanced leakage is expected.[3] These factors outweigh the effect of possible hot hole enhanced leakage,[3] and the negligible hole leakage current is not unexpected.

In conclusion, the electron and hole leakages in a InGaAsP laser emitting at 1.2 and 1.3 μm have been measured directly in the temperature range of 10–32 °C, using a laser-transistor structure. No hole leakage has been observed. On the other hand, electron leakage was found to be substantial in lasers emitting at 1.2 and 1.3 μm. The leakage current was found to be a sensitive function of temperature. Experimental data obtained in this work showed that eliminating the leakage current will result in a 20–30 °K increase in T_0, and a corresponding 20–30% decrease in threshold current. These improvements have been realized by increasing the doping level in the p-InP cladding layer[4,5] and have resulted in lasers with low threshold current and relatively high T_0.[6]

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