Measurement of the effective temperature of majority carriers under injection of hot minority carriers in heterostructures

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We propose and demonstrate a purely electrical method for measuring the effective temperature T_e of majority carriers under the injection of hot minority carriers. The T_e of holes in a thin p-type InGaAs layer, heated by electron injection from an InAlAs layer in a three-terminal lattice-matched heterostructure, was determined by measuring the thermionic emission current of holes over another specially designed InGaAs/InAlAs barrier. At $T=77$ K, we observed an overheating T_e-T of over 50 K, even at moderate injection power levels.

Injection of hot minority carriers is a common phenomenon in modern heterojunction devices. Electrons injected at high energy, corresponding to the conduction band discontinuity, thermalize via optical phonon emission and inelastic scattering by majority holes. As a result, the effective temperature T_e of holes in the active region may significantly depart from the lattice temperature T. The increasing T_e leads to an enhancement of the thermionic flow of holes from the active region and increases the intensity of Auger recombination processes. Overheating of majority carriers may have important consequences for the performance of such heterostructure devices as lasers, bipolar transistors, etc.

It is possible to estimate T_e from the high-energy tails of interband luminescence spectra,[1] when such spectra can be taken from the active region. Recently, we employed the electroluminescence technique to measure the temperature of an electron-hole plasma in complementary real-space transfer transistors at high injection current densities.[2] We observed a strong overheating $\Delta T_e \equiv T_e - T \gtrsim 100$ K. In the present letter, we propose and experimentally demonstrate an *electrical* method for the determination of T_e, based on monitoring the thermionic current of majority carriers. In contrast to electroluminescence experiments, this method (i) does not require a high radiative efficiency of interband recombination and (ii) allows us to estimate ΔT_e at low injection levels.

The three-terminal heterostructure device used in our experiments is illustrated in Fig. 1. The lattice-matched InGaAs/InAlAs heterostructure was grown by molecular beam epitaxy on a conducting InP substrate and processed into devices using optical lithography and selective wet etching. A key fabrication step involved evaporation of self-aligned ohmic contacts to the p-type active layer, as described in Ref. 2. The distance between these contacts was $L=2$ μm. We used devices with the widths $W=10$ and 20 μm, defining the collector area $W\times L$. The total injector area, defined by a mesa etch, was 0.96 and 1.35×10^{-5} cm^2 for 10 and 20 μm devices, respectively.

The bottom of Fig. 1 shows the device band diagram (in the plane that cuts the collector in the middle) under bias. Both ohmic contacts to the active layer are grounded and negative voltages are applied both to the injector ($-V_E$) and the collector ($-V_C$). In the operating regime, electrons are injected into the active layer with an initial kinetic energy equal to the conduction band discontinuity $\Delta E_C=0.5$ eV and holes flow into the collector thermionically over the valence band barrier $\Delta E_V=0.2$ eV (these are generally accepted[3,4] values for the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterosystem). The value of ΔE_V in the present sample was confirmed by studying the temperature dependence of the thermionic current of holes from the active region into the collector at zero injection bias $V_E=0$ and low collector bias $V_C=0.1$ V. Assuming $\Delta E_V=0.2$ eV, the obtained dependence of the collector current $I_C(T)$ in the range $150\lesssim T\lesssim250$ K is in a good agreement with the thermionic model, $I_C=SA^*T^2\exp(-\Phi/kT)$, where S is the barrier area (we studied two type of samples with $S=2$ and 4×10^{-7} cm^2), $A^*\approx60$ A/cm^2 K^2 is the effective Richardson constant, $\Phi=\Delta E_V+E_{Fp}$ is the thermionic barrier for holes, and E_{Fp} is the hole Fermi level in the active region.

Figure 2 shows a typical dependence $I_C(V_C)$ measured at $T=77$ K and different injection current densities J_E. Polarity of the current corresponds to holes flowing into the collector. The collector current nearly saturates at high V_C with a residual increase that can be attributed to a barrier lowering. When the negative potential of the active region

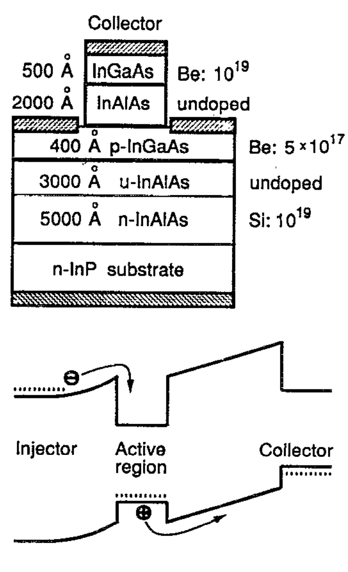

FIG. 1. Structure cross section and the band diagram under bias.

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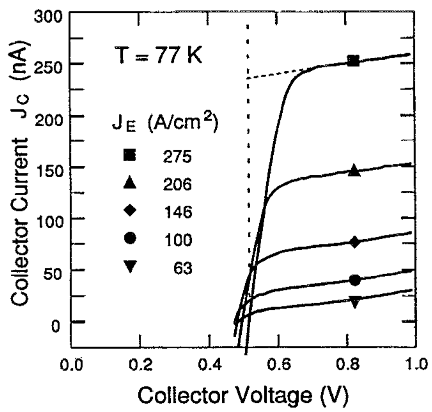

FIG. 2. Dependence of the collector current I_C on the collector voltage V_C for several injection current densities J_E. The collector area is 2 μm×10 μm=2×10^{-7} cm^2. Dashed line illustrates the procedure of extrapolating to the flatband condition.

under the collector is lower than V_C, then the collector current flows in the opposite direction, since the valence band discontinuity does not present a barrier for the flow of holes from the heavily doped collector with no setback layer. The point where I_C changes sign corresponds approximately to the flatband condition. We are using this consideration to extrapolate the thermionic current I_C, measured at higher V_C, to the flatband value. In Fig. 2, the extrapolation is illustrated by the dashed lines for the case J_E=275 A/cm^2.

The extrapolated value of the collector current density J_C is plotted in Fig. 3 against the injection current density J_E. The effective temperature of holes was then estimated by the thermionic formula

$$J_C = A^* T_e^2 e^{-\Phi/kT_e},$$

using the above values of A^* and ΔE_V. The variation of the barrier height $\Phi = \Delta E_V + E_{Fp}$ due to the dependence of E_{Fp}

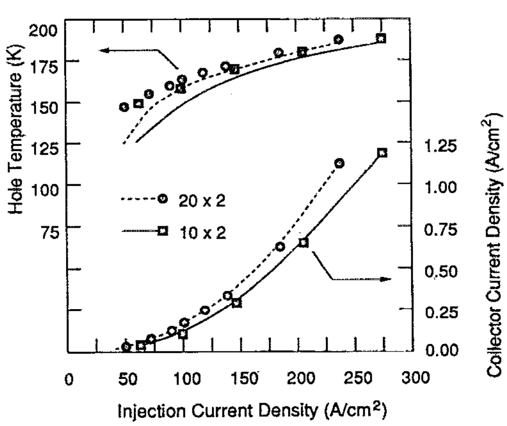

FIG. 3. Dependence of the collector current density J_C at flatbands and the effective hole temperature T_e on the injection current density J_E. In the T_e plot, the symbols designate the temperature calculated that the thermionic emission of holes is the only mechanism of collector current, whereas the lines indicate an adjusted behavior of T_e, assuming a probability of ξ=6×10^{-4} for direct impact emission channels.

on the carrier temperature was included self-consistently. The slight adjustment of E_{Fp} due to the injected carrier density was also included, assuming a carrier lifetime $\tau = 10^{-9}$ s in the active region. Since the estimated injected electron density is less than the majority carrier density $p = 5\times10^{17}$ cm^{-3}, provided by Be doping, the Fermi level E_{Fp} of holes varies little with injection and the possible error in the assumed value of τ has no significant effect on our estimate of T_e.

Thus, calculated T_e is indicated in Fig. 3 by shaded squares and circles for two measured samples. We see that the amount of overheating $\Delta T_e \approx 75$ K is quite substantial even for moderate injection current levels. The curve $T_e(J_E)$ does not seem to extrapolate to 77 K at low J_E; a possible explanation for this will be discussed below. Thermal conductivity estimates[5] show that the expected overheating of the lattice itself is negligible (less than 1 K) in our experiments. This agrees with our earlier observation[2] of no significant lattice heating, deduced from electroluminescence measurements at much higher injection densities. Additional evidence that joule heating effects are negligible comes from the tendency of T_e to saturate with increasing J_E, as well as from the fact that we have seen no superexponential behavior in the injector diode characteristic.

Assuming that the incoming power density equals $(J_E/ed)\Delta E_C$, where d=400 Å is the active layer thickness, we estimate that the energy relaxation time τ_ε of holes in our experiment is more than 10 ps. This appears to be somewhat longer but reasonably close to what one can expect in InGaAs. However, much longer values of τ_ε would be estimated at lower J_E, where we do not observe the expected tendency $T_e \rightarrow T$.

A possible explanation for this discrepancy may be associated with our neglect of direct impact emission of holes by high energy electrons, prior to thermalization. Under the conditions of our experiment, the electron-hole interaction is dominated[6] by scattering channels in which heavy holes are transformed into light holes with high kinetic energy. Presumably, similar considerations apply to channels in which holes end up in the split-off band. Although the probability of a direct emission of such holes should be low, the resultant collector current density scales linear with J_E and should be dominant at low injection, since the thermionic component decreases exponentially. Taking into account this contribution would not alter our estimates for T_e at high injection levels, but those at low injection levels would be drastically changed. Assuming a probability ξ of the direct impact emission we can subtract the contribution $J_C = \xi J_E$ and recalculate the carrier temperature; this procedure is illustrated in Fig. 3, where we assumed $\xi \approx 6\times10^{-4}$. Obviously, thus defined curves $T_e(J_E)$ automatically extrapolate to the lattice temperature as $J_E \rightarrow 0$.

The difference between the calculated temperatures displayed in Fig. 3 and the ambient temperatures, corresponding to the same value of J_C obtained in thermionic experiments, increases with J_E but even at the highest injection levels it isless than 5% of the estimated value of T_e. A possible origin of this discrepancy may be attributed to a dependence of the carrier lifetime on the concentration and the effective temperature.

In conclusion, we proposed and demonstrated an electrical method for measuring the effective carrier temperature in heterostructures. One of the advantages of this method is that it makes possible estimates of majority carrier overheating in structures with a low radiative efficiency of interband transitions. This offers an opportunity for studying the overheating effects in the base of a heterojunction bipolar transistor. Sensitivity of the method allows measurements at low injected power densities.

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