Transport and Optical Properties of Resonant Tunneling Structures

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Received on 23 April, 2001

Transport properties of a GaAs/AlAs superlattice-like double barrier diode are studied in this work as a function of the sample temperature. An activation energy of about 60meV obtained from the Arrhenius plot is in good agreement with the confined level in the central well. Numerical simulations also confirm the importance of bound levels in the Γ and X bands for the resonant tunneling process. The enhancement of photoluminescence as the temperature is increased is also studied. This behavior is associated to the transport properties of holes in the collector contact, which control the supply of minority carriers, which tunnel into the well. The description of the observed results requires the modification of simple known models to take into account the two contributions to the pair generation rate in the well, responsible of the photoluminescence at zero and finite bias.

Resonant tunneling in semiconductor heterostructures [1] continues to deserve interest due to open questions concerning tunneling dynamics and competition with other transport mechanisms. On the other hand, since each sample may show specific fingerprints in the transport properties, resonant tunneling together with thermoionic emission [2,3] are useful spectroscopic techniques for complex potential profiles.

The use of optical measurements such as continuous-wave photoluminescence (PL) has led to a deeper insight on the carrier dynamics, which take place in resonant tunneling diodes (RTD) [4]. However, there is little information about how the transport processes in the contacts affect the photoluminescence spectra.

In this work, we have investigated the transport and optical properties of a GaAs/AlAs superlattice-like double barrier diode. Thermoionic emission and tunneling phenomena are analyzed. The obtained activation energy value agrees with the calculated value of the confined level in the quantum well. The modified Richardson constant value can be explained in terms of the tunneling assisted thermoionic emission process.

An enhancement of the photoluminescence with increasing temperatures is reported for the first time to our best knowledge. This behavior can be attributed to the temperature dependent mobility of holes in the collector spacer layer, which controls the supply of holes that accumulate in the collector/barrier surface.

The samples used in our experiments were grown by molecular beam epitaxy (MBE) on a doped GaAs substrate. The contact layers consist of a 500nm n^+-GaAs (2×10^{18}cm^{-3}) buffer layer, a 50nm n-GaAs (2×10^{16}cm^{-3}) layer and a 2.5nm i-GaAs spacer layer. Each superlattice-like barrier of the sandwiched structure consists of three 0.85nm layers of i-AlAs, separated by 0.85nm i-GaAs layers, with a 5nm well of i-GaAs between both barriers. Two different mesa areas of 3.607×10^{-5}cm^2 (mesa A) and 2.540×10^{-3} cm^2 (mesa B) on the same substrate have been used. An optical window on the top contact was defined on mesa B, in order to perform optical measurements.The superlattice-like double barrier diode is represented in Fig. 1, where the conduction band edges, for the Γ and X minima, are depicted.

Transmission probability calculations, within the effective mass and Transfer matrix approximations [1], reveal resonances associated to quasi-bound states at the structure in Fig. 1, where the lowest one (62meV) in the central quantum well is indicated. Resonances due to quasi-bound states at the superlattice-like bar-

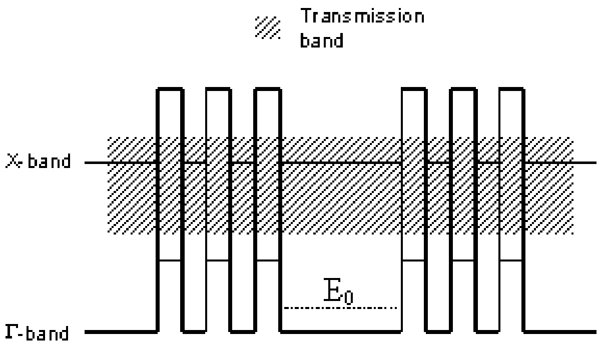

Figure 1. Conduction band edges for the Γ and X minima for the superlattice-like double barrier diode. The lowest quasi-bound state (E_0) is also shown. A transmission band results from resonances due to quasi-bound states at the superlattice-like barrier and excited states of the central well.

rier, as well as excited states of the central well, fall in the energy range also indicated in Fig. 1, building up in fact a wide resonant transmission band. The transmission probabilities are used for calculating current density as a function of applied voltage and temperature in an already known textbook procedure [1]. Current-voltage characteristics in the range 20K-300K were measured on mesas with smaller area contacts (mesa A) to avoid contact series resistance or leakage currents. An Arrhenius-like plot [$\ln(J/T^2)$ vs. $1/T$] was constructed with the measured currents, according to the usual expression for thermoionic emission [2]:

$$J = A^{*}T^{2}exp\left(-\frac{\phi}{KT}\right) \tag{1}$$

where T is the absolute temperature, k is the Boltzmann constant, A^* is the Richardson constant and f is the activation energy. Fig. 2 shows the Arrhenius plot for several voltages lower than the resonance onset (0.3V approximately) together with calculated result for V=1 mV. Fitting the linear part of these curves, the activation energy and pre-factor can be determined.

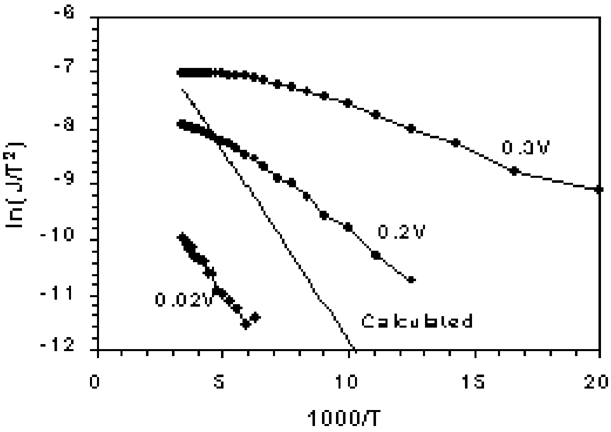

Figure 2. Arrhenius plot for different voltages (0.02, 0.2 and 0.3 V), obtained from the currents measured at different temperatures, and calculated at 1 mV.

Experimental and model calculation results show a reasonable agreement, especially for the activation energy. Undoubtedly, the activated transport is through the lowest bound state in the central well (Fig. 1). The activation energy decreases as the applied voltage is increased, because the bound level is lowered as voltage is applied. The extrapolated value for zero applied voltage is 60.9 meV. The pre-factor values at zero bias obtained from measurements and calculations are orders of magnitude lower than the Richardson constant ($10 \mathrm{Acm}^{-2}\mathrm{K}^{-2}$) given by Eq. (1). This discrepancy is expected since Eq. (1) is valid for unstructured and wide barriers and not for potential profiles like the present one.

Continuous-wave photoluminescence was measured on mesas B at different temperatures. At zero bias, weak PL spectra, due to electron-hole pairs created directly in the well, which recombine radiatively, exhibit the expected temperature dependency: decreasing intensities for increasing temperatures, due to more efficient non-radiative recombination mechanisms as temperature rises.

When bias is applied, electrons are electrically injected from the emitter into the well. Holes photocreated in the collector (near the top contact surface) drift and diffuse, accumulating in the collector/barrier surface and finally tunneling into the well. The hole-tunneling current is proportional to the density of holes: when laser intensity is increased, higher PL intensities are expected. The photoluminescence spectra at 20K as a function of the applied voltage are shown in Fig. 3. Current-voltage characteristics measured at 20K in dark and under illumination conditions are also shown in the inset of Fig. 3.

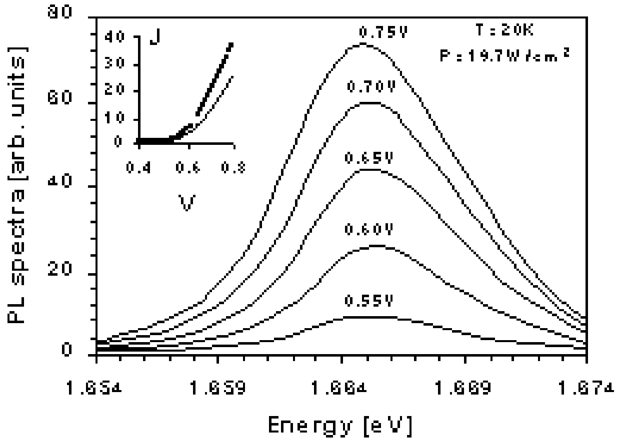

Figure 3. Photoluminescence spectra measured at different bias. Dark (thin line) and illuminated (thick line) current-voltage curves are shown in the inset.

Measurements were performed with different laser intensities. Fig. 4 shows the dependence on temperature of PL intensity and line-width at the tunneling onset, V=0.53V, with a laser intensity, I_L , of

19.7W/cm^2. Instead of the expected decrease in PL intensity with increasing temperatures, due to more efficient non-radiative recombination mechanisms, an anomalous increase of the PL intensity with temperature is observed up to temperatures of about 60K.

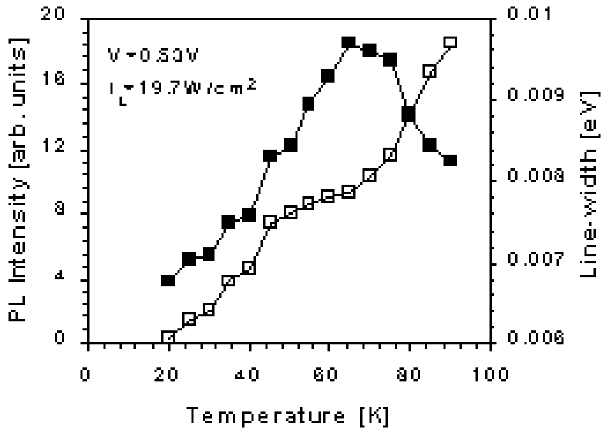

Figure 4. PL intensities (black squares) and line-widths (open squares) as a function of temperature measured at V=0.53V, with a laser intensity I_L=19.7W/cm^2.

In the non-radiative limit [5], the PL intensity is proportional to the sheet electron density in the quantum well, which increases linearly with applied voltage. Higher laser intensities are associated to a larger number of holes available for tunneling, which will recombine radiatively in the well.

The line-width and the current density as functions of applied voltage seem to be independent on laser intensity; both curves exhibit similar spread out for different laser intensities. Thus, a relationship between line-with and current, which does not depend on laser intensity, reflects the fact that the line-width is a function of electron density in the well only, i.e., it does not depend on the holes density in the well.

Therefore, it is possible to discriminate the different behaviors of both carrier species. As shown in Fig. 4, the line-width and consequently the electron density in the well are monotonically increasing functions of temperature for a given voltage. However, this dependence on temperature is too weak to explain the PL behavior, which can be also attributed to the transport properties of holes.

The PL intensity is proportional to the total rate of generation of holes in the quantum well and to the quantum efficiency, η [5]. Two different contributions to the total generation rate in the well must be distinguished: holes directly generated in the well, g_w^p, and injection of holes from the inversion layer by tunneling mechanisms. In steady state, the current of holes tunneling from the inversion layer equals the current of holes generated in the spacer, j_p. Thus, the PL intensity can be written as:

$$I_{PL} = A\,(g_w^p + j_p)\,\eta \qquad (2)$$

At zero bias the second term in bracket in Eq. (2) is zero, and the PL spectra is only due to the recombination of pairs directly generated in the quantum well. In this case, the PL intensity decreases as temperature increases, because of the decreasing quantum efficiency. When voltage is applied, holes photo-created in the collector originate j_p. This current depends on the electric field, and hole mobility in the collector [6]. The mobility is temperature dependent, and at low temperatures, there is a range in which it increases with temperature [6]. In this case, it is expected that the current j_p increase also with temperature as well as PL intensity from Eq. (2), resulting in the observed behavior.

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Acknowledgments

The authors are grateful to J. Nagle, B. Vinter, and Y. Guldner for providing the samples. CNPq, CAPES and FAPESP are also acknowledged for financial support.

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