Charge buildup effects in asymmetric p-type resonant tunneling diodes

Y. Galvão Gobato\textsuperscript{a,c,}\*, M.J.S.P. Brasi\textsuperscript{b}, I. Camps\textsuperscript{a}, H.B. de Carvalho\textsuperscript{b}, L.F. dos Santos\textsuperscript{a}, G.E. Marques\textsuperscript{a}, M. Henini\textsuperscript{c}, L. Eaves\textsuperscript{c}, G. Hill\textsuperscript{d}

\textsuperscript{a}Departamento de Física, UFSCar, 13565-905 São Carlos, SP, Brazil
\textsuperscript{b}Instituto de Física “Gleb Wataghin”, UNICAMP, Campinas-SP 13083-970, Brazil
\textsuperscript{c}School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK
\textsuperscript{d}EPSRC National Centre for III-V Technologies, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK
\textsuperscript{e}Federal University of Santa Catarina-SC-Brazil

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Abstract

We have investigated p-doped GaAs-AlAs resonant tunneling devices with asymmetric barriers under optical excitation. Transport and photoluminescence measurements were performed under identical bias conditions as a function of the light excitation intensity. We have observed the development of additional peaks, induced by illumination, between the main light- and heavy-hole resonances in the current-voltage characteristics ($I(V)$). We describe the behavior of these photo-induced peaks under a magnetic field parallel to the current. We propose that the observed properties are related to resonant tunneling of photoinduced electrons and associated excitonic effects.

The study of resonant tunneling diodes (RTD) is of great interest due to its fundamental character and to the large number of possible applications based on such structures. It is well know that RTD structures can give rise to a significant amount of space charge in the quantum well (QW) \cite{1}. This effect is enhanced in asymmetric devices in which carriers resonantly tunnel into the QW through the emitter barrier and have a smaller transmission coefficient for tunneling out of the well due to a thicker (or higher) collector tunnel barrier. Photoluminescence (PL) spectroscopy is a useful tool to provide important insights into the fundamental properties of an RTD such as tunneling dynamics \cite{2–4}, charge buildup \cite{5}, the degree of conservation of phase coherence according to coherent or sequential models \cite{6,7}, and the properties of photo-excited minority carriers \cite{8}.

In this work, we have studied the influence of light on the $I(V)$ characteristics of $p-i-p$ resonant tunneling diodes. New additional peaks appear in the $I(V)$ curves when the structure is under illumination. These peaks are investigated by magneto-transport and photoluminescence spectroscopy with a magnetic field applied parallel to the current.

The device consists of a 4.2 nm GaAs QW between two AlAs tunnel barriers with thicknesses of 4.5 and 5.7 nm. The same device was previously used to investigate its intrinsic bistability, hole charge buildup and photoluminescence effects \cite{9,10}. The structure was processed into a 400 $\mu$m diameter mesa with a metallic AuGe annular top contact to allow optical measurements under applied bias. A schematic diagram of the device is shown in Fig. 1 for the case in which the substrate is positively biased. Under these conditions, holes tunnel into the well through the thinner barrier and tunnel out the well through the thicker barrier. The device was illuminated with an Ar\textsuperscript{+} ion laser. The sample was mounted in a superconducting magnet and the photoluminescence spectra were recorded using a Spex 500 M single spectrometer with a R5108 Hamamatsu photomultiplier and a photocounting system.

Fig. 2 shows the $I(V)$ characteristics when the structure is illuminated with different laser intensities at 10 K. In the dark, we observe two peaks associated with resonant tunneling through the HH1 and LH1 sub-bands of the QW \cite{10}. Under excitation, the LH1 resonance shifts to higher voltages with increasing laser intensities and we observe the developing of two additional features between the HH1 and LH1 resonance. The photo-induced peaks are labeled P1 and P2. P1 is observed near 0.3 V and its position remains essentially constant. P2 is observed around 0.48 V for low laser intensities, but it shifts to higher voltages when the laser intensity increases. We attribute the origin of P2 to resonant tunneling of photo-generated electrons into the E1 state of the QW.
For low laser intensities and under positive bias, the excitation with light creates electron-hole pairs (see Fig. 1). To understand the origin of peaks P1 and P2, we need to consider the carriers created in the GaAs layer to the left of the left hand barrier. The photo-created holes (majority carriers) are swept out to the heavily doped contact layer and the photo-created electrons (minority carriers) drift towards the QW forming an electron accumulation layer against the left hand barrier. We attribute the P2 photo-induced peak to resonant tunnelling of photo-created electrons into the E1 QW sub-band. For symmetrical samples with an equivalent QW layer, the E1 resonance is usually observed at a bias voltage above the LH1 resonance, in accordance with a simple effective mass calculation for a 4.2 nm QW [10]. In the asymmetrical sample, however, the hole-charge accumulation in the well under positive bias becomes significant due to the thicker barrier that the holes face for tunneling out of the well (see Fig. 1). Hence the peak of the LH1 resonance is shifted to higher voltages [10].

Note however that the threshold of LH1 (see 0 mW in Fig. 3) occurs at ~0.3 V, significantly below P2, corresponding to the E1 electron resonance.

On the other hand, the photocreated electrons which enter the QW can easily tunnel out through the thinner barrier. We therefore do not expect a strong accumulation of electrons in the well and the E1 peak should remain at the same voltage as for the symmetric structure. This situation results in an apparent inversion of the bias positions of the peaks of the resonances in the I(V) characteristics, with the E1 peak appearing below the LH1 peak. The accumulation of photo-created electrons close to the collector barrier further modifies the band bending of the device shifting the LH1 resonant peak to even higher voltages.

We tentatively attribute the P1 resonance to the following mechanism. At 0.3 V, the 0 mW curve shows a significant tunnel current due to the majority holes so we can expect that the QW contains a modest density of holes in the HH1 sub-band. The presence of these holes could provide an additional channel for photoexcited electrons entering the QW from the left side GaAs barrier. Thus electrons could enter the QW and form neutral excitons with these holes in HH1 [11,12]. The voltage required is reduced slightly relative to P2 (=E1) through the Coulombic interaction of the oppositely charged carriers. This mechanism for P1, \(e + h (\text{HH1, QW}) \rightarrow X^0(\text{QW})\) is analogous to that which gives rise to an additional donor-assisted tunneling peak in the I(V) curves of n-type RTDs with a low density of donors in the QW [13].

We have also performed magneto-transport and photoluminescence measurements. Fig. 3 shows the I(V) characteristics in the presence of a magnetic field parallel to the current. The peak P1 remains basically unaltered when the magnetic field is applied to the structure, while the peak P2 shows a splitting under high magnetic fields indicated by the two arrows, with both peaks moving to lower voltages. In a magnetic field applied parallel to the current, the density of
states for electrons in both the emitter and well are split into Landau levels. As a consequence, additional structures in the \( I(V) \) curve are expected due to elastic and inelastic tunnelling processes with both conservation and non-conservation of Landau level index [14]. This process also depends on the charge accumulation in the 2D contact and well. We associate the observed splitting to the agneto-tunnelling of electrons through different Landau levels.

**Fig. 4(a)** shows typical PL spectra from the quantum well for various biases. The PL spectra correspond to an excitonic transition involving the lowest electron and hole states \( E_1-HH_1 \) of the QW. The electrons in the left side GaAs layer drift under the action of the depletion electric field toward the barrier and tunnel to the quantum well. The PL intensity increases with applied bias. At zero bias, PL intensity is only observed for high laser intensities. We have observed a red shift of the PL with increasing bias due to the Stark effect. **Fig. 4(b)** shows the integrated PL intensity from the quantum well as a function of the applied voltage. We observe a good correlation between the integrated PL intensity and the \( I(V) \) characteristics with two clear maxima of the PL intensity at voltages corresponding to the photocurrent peaks \( P_1 \) and \( P_2 \). Under low laser intensities, we expect that the PL intensity should be rather sensitive to the rate at which the minority photo-generated electrons tunnel into the quantum well. In effect, the photo-induced features \( P_1 \) and \( P_2 \) appear as dominant peaks in the PL intensity in accordance with their proposed origin related to tunneling of photoexcited electrons. The fall-off of the PL intensity at high bias is probably due to the increased tunneling rate of carriers out of the QW [3,4].

In summary, we have observed the development of two additional peaks in the \( I(V) \) characteristics of \( p-i-p \) resonant tunneling structures under laser illumination. These photo-generated peaks were investigated by magneto-tunneling and PL spectroscopy. We propose that the origin of the peaks is related to photoinduced electron resonance and to the formation and dissociation of excitons participating in the tunneling processes.

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**References**


