 Determination of carrier density and dynamics via magneto-electroluminescence spectroscopy in resonant tunneling diodes

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We study the magneto-transport and magneto-electroluminescence properties of purely n-doped GaAs/Al\(_{0.6}\)Ga\(_{0.4}\)As resonant tunneling diodes with an In\(_{0.15}\)Ga\(_{0.85}\)As quantum well and emitter prewell. Before the resonant current condition, magneto-transport measurements reveal charge carrier densities comparable for diodes with and without emitter prewell. Landau level splitting is observed in the electroluminescence emission from the emitter prewell enabling the extraction of the charge carrier dynamics. Our findings show that magneto-electroluminescence spectroscopy technique provides useful insights in the charge carrier dynamics of resonant tunneling diodes and is a versatile tool to complement magneto-transport techniques.

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I. INTRODUCTION

Resonant tunneling diodes (RTDs) with their current peak followed by a region of negative differential conductance (NDC)\(^1\)\(^-\)\(^3\) are semiconductor devices with potential applications as, e.g., optoelectronic circuits\(^4\)\(^-\)\(^5\), photodetectors\(^6\)\(^-\)\(^7\), terahertz oscillators\(^8\)\(^-\)\(^9\), and fast switches\(^10\). Understanding the paths through which carriers travel and accumulate along the structure helps to design high quality devices.\(^11\)\(^-\)\(^12\) Heterostructure engineering enables the enhancement and optimization of the RTD figures of merit, such as the peak-to-valley current ratio (PVCR) and peak current density.\(^13\) In that sense, the insertion of an emitter prewell adjacent to the double barrier has proven to be a relevant design recipe.\(^14\)\(^-\)\(^19\) It improves the peak current density and the PVCR at room temperature by suppressing states above the prewell, increasing the charge carrier density close to the emitter barrier and increasing the overlap of the localized states in the prewell and the double barrier quantum well (DBQW) quasi bound states.\(^14\)\(^-\)\(^16\)\(^-\)\(^17\) Furthermore, it has been recently shown that in RTDs based on semiconductors from the 6.1 Å family, the prewell improves the Γ-L-valley energy separation, suppressing the L-valley transport which allows room temperature resonant tunneling operation in this particular material system.\(^18\)\(^-\)\(^19\)

A way to assess the charge carrier dynamics is via spectroscopic techniques with magnetic field such as magneto-photoluminescence (magneto-PL) and/or magneto-electroluminescence (magneto-EL), as they provide distinct information of charge accumulation in different regions within the structure.\(^20\)\(^-\)\(^22\) However, a high amount of charge carriers injected through PL can disturb the system properties. Typically, EL is observed in p-i-n diodes, such as light emitting diodes and solid state lasers.\(^23\) In unipolar doped diodes, as it is the case under consideration here, EL can be observed when minority charge carriers are created, e.g., by impact ionization\(^24\)\(^-\)\(^27\) or potentially by Zener tunneling.\(^28\) Here, we present a complementary approach for investigating the charge carrier dynamics and accumulation in n-i-n GaAs/Al\(_{0.6}\)Ga\(_{0.4}\)As resonant tunneling diodes with In\(_{0.15}\)Ga\(_{0.85}\)As emitter prewells by combining EL and magneto-transport measurements. The results are compared with a conventional GaAs/AlGaAs RTD reference sample without prewell. We show that the optical emission can be used to estimate the charge carrier density in the prewell, even when magneto-transport oscillations are absent. By combining electrical transport measurements with optical spectroscopy techniques, we can address the full map of the carrier density changes along the full operation range of the device.

II. SAMPLE DESIGN AND EXPERIMENTAL SETUP

Magneto-electrical and -optical measurements were performed with the sample placed inside a helium closed-cycle cryostat with superconducting magnet coils (Attocube - Attodyr1000) and the magnetic field oriented parallel to the growth direction. For each magnetic field value, a voltage sweep was performed, and the EL signal and current were measured. All measurements presented in this study were obtained at a nominal temperature of T = 4 K. The optical signal is collimated by an aspheric lens (NA = 0.64) and transmitted along a 50 μm multimode optical fiber, being dispersed by a 75 cm spectrometer and detected by a silicon charged couple device detector (Andor - Shamrock/Idus).

The bandgap energy profiles of the two samples under study, at T = 4 K, are shown in Figure 1(a). The samples were grown by molecular beam epitaxy of an intrinsic GaAs/Al\(_{0.6}\)Ga\(_{0.4}\)As double barrier structure (DBS), followed by a lowly doped (n ≈ 10\(^{17}\) cm\(^{-3}\)) 100 nm-
Both samples present two emission lines related to donor and acceptor levels. The InGaAs sample (blue-dashed line) and Ref-GaAs (red line) EL spectra at (d) forward and (e) reverse bias voltage, the S-InGaAs (Ref-GaAs) peak current density is higher for the prewell-containing heterostructure. The S-InGaAs and Ref-GaAs spectra measured via PL and EL show nearly identical emission lines. For the S-InGaAs sample, the prewell emission (E₁) is more pronounced compared to the GaAs peak, with a peak height of 1.510 and 1.528 for PL and EL, respectively. Both emission lines are almost identical, which indicates that the growth details (except of the prewell and QW) are nearly identical. For the S-InGaAs sample, the prewell emission (E₁) can be seen. Its emission line is more pronounced compared to the GaAs peak, with a peak height of 74% higher than E₃.

The current density-voltage (j(V)) characteristics for Ref-GaAs and S-InGaAs are presented in Fig. 1(c). For forward bias voltage, the S-InGaAs (Ref-GaAs) peak current density is \( j_{res} = 117 \mu A/\mu m^2 \) (\( j_{res} = 87 \mu A/\mu m^2 \)) at \( V_{res} = 2.8 \) V (\( V_{res} = 2.6 \) V), and the PVCR is 8.9 (12.8). As the heterostructure asymmetry leads to the reduction in the absolute value of the peak current density compared to forward bias, and this reduction is more pronounced for the prewell-containing heterostructure (see Ref. [31]).

After surpassing a critical voltage of \( V \geq 8 \) V, electroluminescence emission is observed. To acquire more detailed information about the EL origin, normalized EL spectra for the S-InGaAs and Ref-GaAs obtained at the resonant current conditions (EL at \( V=V_{res} \)) are shown in Figs. 1(d) and (e), at forward and reverse bias voltages, respectively. At forward bias, the S-InGaAs EL spectrum shows five main emission lines, according to Table I. In turn, Ref-GaAs spectrum consists of four emission lines, without the lower energy prewell, as observed for the S-InGaAs sample. The emission lines E₁ for S-InGaAs, and E₂ and E₃ for both heterostructures are lower in energy compared to the PL, probably due to the donor level[29,30] and the bulk GaAs recombination, labeled as E₂ and E₃ on Table I, respectively. Both emission lines are almost identical, which indicates that the growth details (except of the prewell and QW) are nearly identical. For the S-InGaAs sample, the prewell emission (E₁ in Table I) can also be seen. Its emission line is more pronounced compared to the GaAs peak, with a peak height of 74% higher than E₃.

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to the Joule heating. The DBQW emission energy $E_4$ differs between the two samples. With EL measurements we have access to the quantum well states during the resonant tunneling while measuring the I-V. It is not possible to observe DBQW emission line through PL at $V = 0$ V, whereas measuring PL with $V \neq 0$ V, the incident light can disturb the system and change intrinsic charge carrier dynamics and DBQW quantization, due to the excess photogenerated electron-hole pairs.\textsuperscript{32–34} For the Ref-GaAs we can extract the sum of electron and hole quantization energies ($E_{e^-} + E_{h} = 146$ meV) by subtracting $E_4$ from $E_3$, whereas the same is not possible for S-InGaAs as we do not have information from the bottom of InGaAs QW. At reverse bias, both S-InGaAs and Ref-GaAs EL spectra present the GaAs and AlGaAs emission lines, and the DBQW peak is present only for the reference sample. Under reverse bias, electrons are ionized mostly in the highly doped GaAs layer at the substrate side. Generated holes drift through the DBS towards top contact side, and accumulate at the interface between the GaAs and AlGaAs valence band barrier. The presence of $E_3$ and the missing donor emission ($E_2$) suggest electron-hole recombination occurring along the lowly doped GaAs layer. A portion of holes overcome the barrier and reach the optical window. The absence of InGaAs prewell emission at reverse bias indicates that the prewell is completely depleted of electrons.

The calculated impact ionization threshold is $E_{GaAs}^{th} = 1.80$ eV for the GaAs, and $E_{AlGaAs}^{th} = 2.08$ eV for the AlGaAs optical window, obtained by considering energy and momentum conservation in the transitions during ionization processes.\textsuperscript{27,35} For both heterostructures the onset for EL starts at $V = 1.8$ V due to $E_{GaAs}^{th}$. The AlGaAs peak ($E_5$) is present at voltage values $V > 2.0$ V, which means that a fraction of electrons travel ballistically through the drift region without impact ionization or scattering events before reaching the AlGaAs optical window, and, as this region is not well defined, EL onset variations may occur. As the applied electric field increases, more holes are created at the optical window, increasing the intensity of emission $E_5$. At higher bias voltages ($V > 3.5$ V) $E_5$ starts to vanish because generated holes at the AlGaAs region are swiped out towards the DBQW before they recombine with electrons. The light emission from the DBQW ($E_4$) is also present at low bias voltages and increases up to the resonance condition as the quantum well gets populated. After the resonance voltage, the $E_4$ emission abruptly drops because, in the off-resonance condition, the electron carrier density inside the quantum well is significantly reduced.\textsuperscript{36}

At low bias voltages ($2.0$ V) the prewell emission ($E_1$) dominates. Holes created at the top-contact side drift towards the DBS and either recombine with electrons in the lowly doped (see Fig. 1(a)) and/or intrinsic GaAs region ($E_4$), DBQW ($E_4$) or tunnel through the DBS. Here, they recombine with electrons in the prewell ($E_1$) and with electrons in the highly doped GaAs region of the emitter side ($E_2$). On the other hand, as the Ref-GaAs does not have a prewell, the holes recombine mostly with electrons from GaAs layers. When the bias voltage is above the resonance ($V \geq 3.0$ V) electron charge build-up in the prewell is supported, which results in an increasing asymmetry of its EL emission ($E_1$). Furthermore, holes are more likely to swipe into the highly doped region at the substrate side and recombine with electrons, and the emission $E_2$ becomes more predominant compared to $E_4$.

Ref-GaAs and S-InGaAs EL integrated intensity vs. voltage are shown in Fig. 2(b). A gray shadow of the S-InGaAs I-V characteristics is also plotted. Both intensity curves are comparable, with a peak at resonance, followed by an intensity drop in the valley region. At high voltages the intensity increases again. Within the NDC region, the RTD without prewell presents an EL intensity decrease of almost three orders of magnitude. One order of magnitude reduction is observed for S-InGaAs. We have demonstrated, in a recent work, that higher EL peak-to-valley ratio (PVR) for Ref-GaAs is due to a competition between coherent and sequential tunneling channels.\textsuperscript{24} The smaller optical PVR for the S-InGaAs heterostructure at cryogenic temperatures is probably caused by the prewell charge build-up. By analyzing the prewell peak position on Fig. 2(c), obtained at the peak maximum intensity, we observe an increase from 1.445 eV to 1.453 eV before $2.0$ V and then it becomes nearly constant up to the resonant voltage due to an electrostatic feedback.

![FIG. 2. (a) Normalized EL spectra for S-InGaAs (blue circles) and Ref-GaAs (red circles) for different bias voltages. Ref-GaAs emissions are normalized according to the maximum of S-InGaAs, disregarding the prewell emission. (b) S-InGaAs (blue opened circles) and Ref-GaAs (red opened triangles) integrated intensity vs. bias voltage. A gray shadow of the S-InGaAs I-V characteristics is also plotted. (c) Prewell peak position as function of voltage (blue dots).](image-url)
screening the prewell (see Refs. [21] and [37]). After the resonance, we can observe a constant redshift of the prewell energy of about $-4.40 \pm 0.24 \text{ meV/V}$. 

Figures 3(a) and (b) present the two-dimensional intensity maps of S-InGaAs EL spectra as function of applied magnetic field and voltage. The top and bottom panels correspond to the measurements performed before and after the resonance peak, respectively.

We can resolve a fan-like pattern of Landau levels (LLs) in the EL spreading out from the emitter prewell emission line as the magnetic field increases within a wide voltage range. On the other hand, no LL splitting is observed for the DBQW state. LLs are also absent from Ref-GaAs heterostructure (not shown). The differences of LLs splitting before and after the resonant condition is worth noting. At voltages up to the resonance, we observe a picture in which the levels are not well resolved. This indicates that the quasi-Fermi energy at the prewell ($E_{F\text{prewell}}$) is close to the prewell ground state, as DBQW is supporting strong charge build-up due to resonant conditions, and electrons tunnel through the double barrier rather than accumulate in the prewell. On the off-resonance case, the energy levels misalignment quenches the resonant tunneling rate and electrons accumulate in the prewell, raising $E_{F\text{prewell}}$ at higher energies.

A peculiar feature is also observed at the voltages from 3.1 V to 3.5 V (Fig. 3(b)) where the EL intensity tends to increase with magnetic field, whereas at voltages below and above this voltage range the opposite occurs. The Ref-GaAs structure EL intensity at this voltage (not shown) increases with magnetic field as well.

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From the experimental dependencies of the transition energies on the magnetic field, we calculate the energy separation of the LLs using a two-band model. In this model the energies of the Landau transitions between a parabolic band for the holes and the non-parabolic band for the electrons are given by the equation

$$ E_N = \frac{E_g}{2} + \sqrt{\left( \frac{E_g}{2} + E_0 \right)^2 + E_g \left( N + \frac{1}{2} \right) \frac{\hbar e B}{m_{0,e}}} + \left( N + \frac{1}{2} \right) \frac{\hbar e B}{m_{0,h}} + H_0 $$

where $m_{0,e} = 0.071m_0$ and $m_{0,h} = 0.15m_0$ are the effective masses of the In$_{0.15}$Ga$_{0.85}$As conduction and valence bands, respectively; $E_g$ is the bandgap energy of the In$_{0.15}$Ga$_{0.85}$As prewell; $N$ is the Landau level quantum number; $E_0$ and $H_0$ are the electron and hole subband energies. The results of the calculation are shown as solid lines in the colorplots of Fig. 3 at 2.4 V and 3.4 V, where it can be seen that all Landau energies fit well with the experiment.

Fig. 4(a) shows current density characteristics taken at zero magnetic field (dashed lines) and $B = 9$ T (solid lines) for Ref-GaAs and S-InGaAs colored red and blue, respectively. The S-InGaAs (Ref-GaAs) resonance current density peak decreases from 117 $\mu\text{A/}\mu\text{m}^2$ (93 $\mu\text{A/}\mu\text{m}^2$) to 105 $\mu\text{A/}\mu\text{m}^2$ (74 $\mu\text{A/}\mu\text{m}^2$) and shifts from 2.80 V (2.95 V) to 3.05 V (3.03 V) by sweeping the magnetic field from 0 to 9 T. PVCR decreases from 8.9 (14.2) to 8.5 (11.2) driven by the reduction in the peak current density. At $V = 3.2$ V a small shoulder in the current density is observed, as shown in insets of Fig. 4(a). Figs. 4(b) and 4(c) present the current density difference between transport measurements with and without an applied magnetic field (from 1 T to 9 T) in the range between 3.08 and 3.40 V, for Ref-GaAs and S-InGaAs,
FIG. 4. (a) Current-voltage characteristics for Ref-GaAs (red) and S-InGaAs (blue) obtained at $B = 0$ T (dashed lines) and 9 T (solid lines). Insets represent a zoom-in of the voltage range between 3.0 V and 3.8 V. A small shoulder is observed around 3.2 V. Current density difference between curves with applied magnetic field ($j(B) - j(0)$), for (b) Ref-GaAs and (c) S-InGaAs, from 3.08 V to 3.40 V. A current density peak emerges and changes position with the magnetic field. There is a correlation with the EL intensity increase between 3.1 V and 3.5 V observed in Fig. 3(b). The increased current density with magnetic field leads to a higher hole generation rate and, therefore, a subsequent luminescent signal increase. It is important to note that the light emission and current density increase with magnetic field are not proportional. This is because the hole generation rate is enhanced when the system is in the on-resonance regime.

We can extract relevant quantitative information on the charge accumulation by combining both the transport and optical results under magnetic field. First we focus on the current versus magnetic field, from which we can estimate the charge carrier density at the prewell. From the S-InGaAs (Ref-GaAs) I-V characteristics at several magnetic fields, the normalized current oscillations are plotted as function of the inverse field, $1/B$, as blue (red) lines, presented in Fig. 5(a). Once we measured current-voltage characteristics at several magnetic field values, we extracted the current as function of magnetic field by transposing the data and fixing the voltage. Oscillations are visible in both samples, which are the signature of two-dimensional electron gas (2DEG) quantization due to the crossing of the Landau levels and the Fermi energy. In the case of S-InGaAs these oscillations are produced by the InGaAs emitter prewell Landau quantization, and they can be resolved from 0.75 V to 1.95 V, after which we are not able to see them. For the Ref-GaAs sample, an emitter triangular prewell is formed due to the band structure bending with electric field and the oscillations are present from 1 V to 2.2 V, and can be further resolved after the resonance presenting a higher frequency from 4 V and forward.

FIG. 5. (a) Normalized current oscillations as function of magnetic field for several bias voltage values from 1.0 V up to 5.5 V for S-InGaAs (blue lines) and Ref-GaAs (red lines), offseted for clarity. Voltages before (after) the resonance condition are located below (above) the horizontal dashed line. The inset shows a zoom-in for 4.0 V up to 5.5 V. (b) Charge carrier density as function of voltage extracted from the EL emission for S-InGaAs (opened blue circles), and from the current oscillations, for S-InGaAs and Ref-GaAs in blue and red dots, respectively. The vertical dashed line refers to the resonance voltage.

Figure 5(b) presents the charge carrier density inside the (triangular) emitter prewell ($\eta_{\text{prewell}}$) as function of the voltage for the S-InGaAs (Ref-GaAs) obtained through the current oscillations with period $\Delta(1/B)^{20,47,48}$ as

$$\eta_{\text{prewell}} = \frac{e}{\hbar \pi \Delta(1/B)},$$

Note that, before resonance, the calculated charge carrier densities in both samples are similar as they were grown with the same donor profile. In the off-resonance case the charge carrier density can be calculated for Ref-GaAs after 4 V, which is observed to be higher than on-resonance due to the charge build-up at the emitter barrier. It is not possible to calculate the charge carrier density for voltages above the resonance for the S-InGaAs sample using magneto-transport measurements since the oscillations are not observed. The lack of current oscillation after resonance is probably due to the incoherent trans-
port, such as sidewall leakage, thermionic emission, incoherent tunneling, which are not influenced by magnetic field. For the Ref-GaAs, the oscillation observed from 4 V indicate coherent transport which can be associated to the tunneling through excited DBQW levels. The S-InGaAs coherent transport current oscillations would appear after 6 V, beyond the experimental voltage range. Nevertheless, in this scenario, electroluminescence measurements can be useful for the charge build-up investigation and complete the map of carrier density changes along the full operation range of the device. By considering that the charge carriers are thermalized, we can calculate the density of the 2D states at the prewell as follows

$$\eta_{prewell} = \frac{E_{F, prewell}^2 m^*}{\hbar^2 \pi}$$ (3)

By analyzing the prewell emission before resonance (Fig. 3(a)), we can define the quasi-Fermi energy as the difference between the peak position and the energy at half maximum, at $B = 0$ T. After resonance (Fig. 3(b)), the prewell emission asymmetry interferes with the donor emission line $E_D$, making it difficult to determine the quasi-Fermi energy with the prior method, we thus developed an alternative method. By analyzing the EL intensity as function of the magnetic field for each energy value, the Landau levels oscillations are clearly resolved. The $E_{F, prewell}$ varies with magnetic field, we determine it as the difference between $E_1$ and the energy position at which no more oscillations are detected and extrapolate it down to 0 T.

The charge carrier density extracted from the EL measurements using that method is depicted in Fig. 5(b) as open blue circles. The error bars before and after the resonance are estimated considering, respectively, the spectral noise and the donor emission linewidth due to the interference between the LLs and $E_D$. As one can see, before resonance these results coincide within the same range of the blue dots, and after resonance, we obtained a charge carrier density similar to the Ref-GaAs sample. These agreements are indications that the optical emission can also be used to estimate these quantitative features.

IV. CONCLUSIONS

In summary, we investigate carrier dynamics of a GaAs/AlGaAs resonant tunneling diode with InGaAs emitter prewell and QW combining transport measurements and electroluminescence. A conventional GaAs/AlGaAs RTD was used as a reference sample, to further study the effects of the S-InGaAs heterostructure.

With electroluminescence we observed internal charge carrier transport processes without the need for photoluminescence. This is particularly important as RTDs have been shown to exhibit transport characteristics that can be very sensitive to illumination. Furthermore, the charge carrier densities obtained for both samples through the current magneto-oscillations are comparable before the resonance, however the lack of clear oscillation after resonance for the S-InGaAs sample prevents the determination of this parameter. We have shown the Landau levels quantization in the emitter prewell of a resonant tunneling diode via EL. Finally, we have estimated the charge carrier density in the prewell by analyzing this same EL emission, and have shown a good agreement with the transport measurements. These results give valuable information on the charge carrier build-up, which can be useful on device fabrication for RTD devices optimization.

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