Impact of band to band tunneling in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ tunnel diodes on the deep level transient spectra

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Peculiar features of the deep level transient spectroscopy (DLTS) measurements on p^+-i-n^+ $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ tunnel diodes are explained. It is shown that due to the high doping of the tunnel diodes and the large band to band tunneling conductance under reverse bias, the DLTS spectrum is prone to erroneous interpretations. We discuss a procedure to identify the cause. In the tunnel diodes, a donor-like hole trap (H1) associated with a point defect, with an activation energy of $E_V + 0.09$ eV and capture cross-section of $(2.4 \pm 1) \times 10^{-19} \text{ cm}^2$ is identified. In addition to the thermal emission, we report the observation of tunneling emission of holes from the H1 trap.

For n -channel III-V Tunnel FET (TFET), theory predicts steep sub-threshold slope (SS) due to the electron energy filtering mechanism of direct band to band tunneling (BTBT)^{1–5}. Nonetheless, the experimental demonstrations fall short because a thermally generated leakage current is encountered^{1,5,6}. The source of the leakage current is often ascribed to defects, originating from the quality of the epitaxial layers (e.g. bulk defects), of the hetero-interfaces (e.g. interface states) and/or from the fabrication process (e.g. surface states)^{1,5–9}. Therefore, an increased knowledge on the type of defects and their associated currents is needed to improve the experimental TFET's performance. In this work, $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ tunnel diodes grown using molecular beam epitaxy (MBE) on state-of-the-art high purity InP substrates are studied, and bulk defects in $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ are analyzed.

Nominally lattice-matched $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}/\text{InP}$ heterostructures have broad interest and are extensively studied for p - i - n photodiodes for long wavelength ($\lambda = 1 - 1.6 \mu\text{m}$) light-wave communication. In photodiodes, $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ is used as a light absorbing layer¹⁰ and therefore is lightly doped to ensure large depletion widths. In order to obtain information about the defects in the $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ absorption layer, deep level transient spectroscopy (DLTS) has been widely used^{11–19}. In addition to the impurity levels (e.g. Fe related acceptor^{19–22}) and process-related defects in MBE grown $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ²³, native-defects which are independent of the growth technique have also been identified, e.g. the EL2 defect^{16,17,24–26}. A few traps whose origin is unknown have also been found, e.g. at $E_C - (0.16 \pm 0.02)$ ^{10,11,27,28} and at $E_C - (0.10 \pm 0.02)$ ^{12,14,29}, $E_V + (0.11 \pm 0.02)$ ^{30–33}.

Contrarily to the photodiodes, the tunnel diodes used in this work are designed with degenerate p^+ and n^+ $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ regions, to ensure higher tunneling probabilities. Unfortunately, no reports exists providing information about experimentally identified defects in degen-

FIG. 1. (a) Cross-sectional schematic of the p^+-i-n^+ $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ tunnel diode. The epitaxial-layer thicknesses are nominal, based on previous growth experiments. The dopant concentrations are as measured by secondary ion mass spectroscopy (SIMS) and are an average of 2 measurements. (b) Doping profile as obtained from SIMS. Solid lines show the corrected profiles.

erately doped $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ and/or in tunnel diodes of any material system, using DLTS. Part of the reason is the increased complexity, because in tunnel diodes, due to large BTBT conductance (G) under reverse bias, the capacitive admittance is no longer a correct representation of the diode's junction capacitance. Therefore, the DLTS technique which is based on capacitance transients requires re-consideration of certain assumptions.

In this letter, first we discuss the restrictions of the DLTS technique when employed for degenerately doped tunnel diodes, and propose a method to monitor the correctness of the DLTS spectra. Thereafter, we identify defects in the p^+-i-n^+ $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ homo-junction tunnel diodes, schematically shown in Fig. 1. The diode area is defined using mesa-etch ($\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}::1:3:1000$) with Mo/Al top contacts as hard mask. The etch pit density (EPD), representative of the density of threading dislocations in the InP substrate is less than $\sim 5 \times 10^3 \text{ cm}^{-2}$. A lattice mismatch of less than 10^{-4} is expected, based on previous growth experiments. Fig. 1b shows the depth profile of Silicon (N_{Si}) and Beryllium (N_{Be}) atoms, which are used as n -type and p -type dopants in

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FIG. 2. (a) Circuit representation of a reverse biased p^+-i-n^+ diode and (b) the parallel equivalent circuit. C_p and G_p are parallel capacitance and conductance, respectively. (c) Junction capacitance (C) of an abrupt p^-n^+ junction $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ diode, obtained using Sentaurus Device (Version 2014.09). The doping of the n -type region is set as $N_D = 2 \times 10^{19} \text{ cm}^{-3}$ and Fermi-Dirac statistics are used. The plot also shows the restriction imposed by r_s for two device areas (i.e. $r_s \ll (\omega C)^{-1}$). D is the contact diameter.

$\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$. The nominally intrinsic region, ‘i’, has a background p -type doping (N_{Be}) of $2 \times 10^{17} \text{ cm}^{-3}$. It is to be noted that for the given measurement conditions, the detection limit of the Si atoms is $2 \times 10^{17} \text{ cm}^{-3}$. The N_{Si} is therefore corrected as shown in Fig. 1b to $1 \times 10^{16} \text{ cm}^{-3}$, a value obtained using other SIMS measurements. The space charge region extend through out the ‘i’ region (which is un-intentionally p -type doped) and partially in the p^+ region. This indicates that in DLTS experiments the majority carrier (hole) traps are probed. The bias is applied to the n^+ $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ and is therefore denoted as V_n . The reverse bias is abbreviated as V_{nR} .

Figure 2a shows the circuit representation of a p^+-i-n^+ tunnel diode in reverse bias, constituting of a junction capacitance (C), a junction conductance (G) and a series resistance (r_s). The DLTS capacitance meter (Boonton 7200 Capacitance Bridge) typically assumes the device to be represented by its parallel equivalent, as shown in Fig. 2b. The measured parallel capacitance (C_p) is obtained from the imaginary part of the complex admittance and is given by Eq. 1 [Ref. 34]. ω is the angular frequency. The change in parallel capacitance (ΔC_p), i.e. capacitance transient as measured using a DLTS system, is given by Eq. 2. ΔC is the change in junction capacitance due to the carrier trapping³⁵.

$$C_p = \frac{C}{(1 + r_s G)^2 + (\omega r_s C)^2} \quad (1)$$

$$\Delta C_p = \frac{\Delta C}{(1 + r_s G)^2 + (\omega r_s C)^2} \left[1 - \frac{2(\omega r_s C)^2}{(1 + r_s G)^2 + (\omega r_s C)^2} \right] \quad (2)$$

Eq. 2 can be re-written as Eq. 3, where Q is the quality factor³⁶ (discussed later) of the parallel circuit, given by Eq. 4.

$$\Delta C_p = \frac{\Delta C}{(1 + r_s G)^2} \frac{(1 - Q^2)}{(1 + Q^2)^2} \quad (3)$$

$$Q = \frac{\omega r_s C}{1 + r_s G} \quad (4)$$

In an ideal case, when $r_s = 0$, the parallel capacitance is the correct representation of the junction capacitance (i.e. $C_p = C$), even in the presence of leakage current (i.e. $G \neq 0$). This is deduced using Eq. 1. However, in reality $r_s \neq 0$, due to parasitics such as contact resistance⁸. Therefore, in order to ensure that the capacitive admittance is the dominant circuit element, the measurement of the junction capacitance (Eq. 1) must meet two requirements concurrently:

1. $r_s \ll (\omega C)^{-1}$
2. $r_s G \ll 1$

Since an ideal ‘i’ region is not obtained in our device (Fig. 1b), the p^+-i-n^+ diode effectively becomes a $p^+-p^-n^+$ diode. Therefore for simplicity, Fig. 2c show the simulated junction capacitance of a p^-n^+ $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ tunnel diode, with an abrupt junction as a function of the doping concentration (N_A). C increases with device area (A) and doping (N_A). In accordance, the maximum acceptable series resistance to meet the condition, $r_s \ll (\omega C)^{-1}$, decreases and the 1st condition is subjected to violation. Typically the work-around methods are to (i) reduce r_s by minimizing the thickness of the series resistance region by applying a $|V_{nR}|$ of high magnitude (Fig. 2c) or (ii) to perform the capacitance measurements at a lower frequency, f , (since r_s is inversely proportional to ωC)^{37,38}, or (iii) use a small area device. Tunnel diodes are limited by the magnitude of the reverse bias which can be applied owing to increasing G , as discussed later. Furthermore, f is restricted to 1 MHz, which is the operating frequency of the commercial DLTS system. We therefore adopt a diode with a small area ($D = 200 \mu\text{m}$), for our study. Experimentally, from the slope of the current-voltage (I - V) characteristics at large forward bias, where the diode is fully turned on and exhibits a small differential resistance³⁵, we estimate r_s of 75 Ω for our device. The expected C is 311 nF at 0.04 V (i.e. $(\omega C)^{-1} = 1 \times 10^4 \Omega$), and therefore the condition $r_s \ll (\omega C)^{-1}$ is met.

The impact of high series resistance (i.e. $r_s \gg (\omega C)^{-1}$) on the DLTS spectra has been reported previously, but only for lowly doped layers³⁷⁻⁴². Due to low doping, r_s was high and in the cases where Q was greater than 1, the observed capacitance transient (associated with majority carriers) became negative^{38,40,41}, as expected from Eq. 3. Nonetheless, in all reports³⁷⁻⁴² it was presumed that $r_s G \ll 1$ and correspondingly Q was approximated as $\omega r_s C$ and C_p was approximated as C/Q^2 . The devices under test were either lowly doped Schottky diodes or MOS capacitors. In these devices, the magnitude of leakage current is restricted to the minority carrier generation, due to which G is small and this permits the assumption of $r_s G \ll 1$. However, this approximation cannot be applied to a tunnel diode. This is because,

FIG. 3. (a) Measured leakage current at the given reverse bias as a function of temperature, for the $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ homo-junction tunnel diode of Fig. 1a, with a contact diameter of $200\ \mu\text{m}$ ($A = 3.1 \times 10^{-4}\ \text{cm}^2$). (b) Arrhenius plot.

in the case of the heavily doped p^+-i-n^+ tunnel diodes, the BTBT begins at very small reverse biases. Figure 3a shows the leakage current in the diode, as a function of temperature (T). Visibly, at the higher bias, the magnitude of current is high due to the increased BTBT generation rate, which leads to $r_s G \gg 1$.

Using an Arrhenius plot, the activation energy (E_A) is extracted as shown in Fig. 3b. For $V_{nR} = 0.04\ \text{V}$ and at low temperatures, the thermal generation of carriers via traps is impeded. As a result, for $T \leq 210\ \text{K}$, the E_A is found to be less than or equal to $0.03\ \text{eV}$, and is associated with BTBT. At higher temperatures, an E_A of $0.09 \pm 0.01\ \text{eV}$ is obtained, which is deeper than the typical activation energies of shallow dopant atoms³⁵ ($\sim 0.01\ \text{eV}$). This suggests the presence of a trap state, leading to thermally generated current. For higher reverse bias, the E_A remains below $0.06\ \text{eV}$ in the entire temperature range, indicating that the carrier generation is dominated by nearly T -independent tunneling of carriers.

In order to obtain the signature of the traps, we use DLTS. Figure 4a, shows the measured DLTS spectrum at a reverse bias of $0.2\ \text{V}$ and $0.4\ \text{V}$. Visibly, the spectrum changes sign at the inversion temperatures (T_{inv}) of $190\ \text{K}$ and $120\ \text{K}$, respectively. As explained below, if caution is not exercised, the negative ΔC can be erroneously interpreted as originating from the emission from a minority trap, with field dependent emission rate. Figure 4b shows the ratio of $(1 + r_s G)^2 \Delta C_p / \Delta C$ as a function of Q , analytically obtained using Eq. 3. In accordance with Eq. 3, the spectra will change sign for $Q > 1$, irrespective of the values of r_s and G . Evidently, in order to estimate the impact of high conductance on the DLTS spectra, Q must be monitored.

Due to increasing leakage current (Fig 3a), the measured capacitance (C_p) decreases with temperature (Eq. 1), as seen in Fig. 4c. This can be considered as a fingerprint of the Q -effect. It is assumed that the plateau represents the ideal junction capacitance (C), as suggested by Simoen *et. al.*⁴¹. Q is determined as a function of temperature using Eq. 3, and is shown in Fig. 4d. The conductance is approximated from the I-V curve. For

FIG. 4. (a) DLTS spectra at two different reverse biases (b) $(1 + r_s G)^2 \Delta C_p / \Delta C$ as a function of the quality factor, Q . (c) Measured parallel capacitance as a function of temperature (d) Q -factor as a function of temperature.

e.g. $G = 1.9 \times 10^{-5}\ \Omega^{-1}$, at $V_{nR} = 0.4\ \text{V}$ at $78\ \text{K}$. As visible in Fig. 4d, Q becomes greater than 1 at a T above $233\ \text{K}$, thereby confirming that the negative amplitude in the DLTS spectrum is a manifestation of the circuit parameters. The cross-over temperature is reduced to $135\ \text{K}$ at the higher bias of $0.4\ \text{V}$, due to higher G and lower plateau value. The quantitative discrepancies in the values of temperature at which inversion occurs (T_{inv}) in the DLTS spectra and cross-over in the Q - T plot, is ascribed to (i) deviation of the ideal C from the plateau value (ii) the neglect of higher order terms in Eq. 2.⁴⁰

In order to characterize the traps in the tunnel diode in a reliable way, a very small bias ($V_{nR} = 0.04\ \text{V}$) is applied. Consequently, the BTBT leakage current is decreased by nearly two orders of magnitude, which reduces the impact of G (Fig. 3). As a result, the negative transient signal is found to disappear, as shown in the DLTS spectra in Fig. 5a. Furthermore, the peak position changes with the period width, T_W , indicating that the emission rate is temperature dependent. The peak is associated with a hole trap (H1) with an activation energy of $0.09 \pm 0.02\ \text{eV}$ from the valence band edge and a hole capture cross-section (σ_p) of $(2.4 \pm 1) \times 10^{-19}\ \text{cm}^2$, as obtained from the Arrhenius analysis (Fig. 5b). Owing to the small σ_p it is concluded that the H1 trap is repulsive and donor-like. The E_A of the H1 defect is in agreement with that obtained from I-V analysis (Fig. 3b), at smaller bias ($V_{nR} = 0.04\ \text{V}$) and higher temperatures, where the thermally generated current dominates the BTBT current. A simulated point-defect peak (solid line) is also shown in Fig. 5a, which is in good agreement with the experimen-

FIG. 5. DLTS spectra showing the H1 trap. ■ and ○ show the experimental data at different period widths. The dashed and solid lines show the simulated spectra, with and without consideration of temperature independent emission (e_{Ti}) associated with tunneling, respectively. (b) Arrhenius plot for the H1 trap. v_{th} is the thermal velocity and N_V is the valence band density of states. (c) Schematic representation of defect-to-band tunneling from the H1 trap. The band diagram is simulated at V_{nR} of 0.04 V, using Sentaurus Device from Synopsys (Version 2014.09). The trap level in $n^+ \text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ is not measured in this work and is therefore shown for illustrative purposes.

tal peak position. A perfect fit to the experimental data, is obtained by assuming a T-independent emission rate ($e_{Ti} = 1/\tau_{Ti}$), in addition to the T-dependent emission from the trap (e_p). As a result, the total emission rate (e) and corresponding time constant (τ) are given by Eq. 5 and Eq. 6, respectively.

$$e = e_p + e_{Ti} \quad (5)$$

$$\tau = \frac{\tau_p \tau_{Ti}}{\tau_p + \tau_{Ti}} \quad (6)$$

The origin of e_{Ti} most probably is trap to band tunneling. At low temperatures, the thermal emission of captured holes competes with the field assisted hole emission from H1 to the valence band, as schematically depicted in Fig. 5c. As a result, the T-independent emission rate ($e_{Ti} = 833 \text{ s}^{-1}$), is higher than the thermal emission rate at low temperatures, where $e_p = 0.2 \text{ s}^{-1}$ at 70 K, 77 s^{-1} at 100 K and 2153 s^{-1} at 130 K. A similar tunneling emission of carriers in competition with the thermal emission, can be found in previous reports on quantum dots^{43–45}.

The T-independent emission is also already observable in Fig. 3b, where irrespective of the reverse bias, a very small E_A is observed at low temperatures, indi-

FIG. 6. At 76 K, (a) Isothermal spectra (b) temperature independent time constant as a function of electric field (ξ).

cating nearly T-independent tunneling of the carriers. In order to experimentally further verify the presence of T-independent emission, the DLTS amplitude was recorded at 76 K, as a function of the transient time constant (by varying T_W), as shown in Fig. 6. A peak is obtained when the transient time constant equals the measurement system's preset time constant. The abscissa corresponding to the peak, is therefore equivalent to τ (Eq. 6). τ_p of 1.04 s is obtained by extrapolating the Arrhenius plot to 76 K (Fig. 5b). τ_{Ti} is then obtained as a function of electric field (ξ) using Eq. 6 and Fig. 6a. ξ is obtained at every bias using device simulations. As shown in Fig. 6b, τ_{Ti} decreases with increasing ξ , as expected for a process involving tunneling of carriers⁴⁴.

In the past, it has been proposed that the traps in (In,Ga)As associated with arsenic vacancy, group III (In or Ga) interstitials or an arsenic antisite, will behave as donor-like hole traps in p-type (In,Ga)As⁴⁶. Pelloie *et al.* have found a hole trap similar to H1, in an $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ layer with an E_A of 0.08 eV and a small σ_p of $6 \times 10^{-20} \text{ cm}^{-2}$. In refs [30–32] a similar trap where the level was 0.11 eV deep, has also been reported. The origin of the trap state cannot be determined at the moment, and a dedicated study is needed to obtain more information on this trap. Based on *ab-initio* calculations, also employing the correction of many-body perturbation theory, the H1 trap could be associated with a gallium vacancy level or gallium antisite^{15,47,48}.

In conclusion, the DLTS spectra of the tunnel diodes change sign due to the high tunneling conductance. For the DLTS experiment using a tunnel diode, the usual assumption of sample impedance reducing to a pure capacitance, is no longer valid. The impact of the BTBT conductance can be verified by monitoring the quality factor, Q , of the circuit. By applying a very small quiescent reverse bias, which allows to reliably measure the junction capacitance by limiting the tunneling conductance, a hole trap present in the p-type $\text{In}_{0.47}\text{Ga}_{0.53}\text{As}$ is detected. The H1 trap is donor-like and lies at $0.09 \pm 0.02 \text{ eV}$ from the valence band edge, with a capture cross-section of $(2.4 \pm 1) \times 10^{-19} \text{ cm}^{-2}$. Temperature independent tunneling of holes from the H1 trap is also observed in the DLTS spectra.

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