pnp resonant tunneling light emitting transistor

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A *pnp* bipolar resonant tunneling transistor is realized using a base consisting of an *n*-type modulation doped quantum-well layer next to a double-barrier tunneling structure. Electrons are injected from the quantum-well base layer into the tunneling structure, leading to quantum-well light emission when they recombine with holes from the emitter. This optical output, which is modulated by the base voltage, persists in the negative differential resistance region of the current-voltage characteristics where the hole current is in oscillation. This opens possibilities for using this transistor as a high frequency electro-optical heterodyne convertor.

Recently, the bipolar resonant tunneling light emitting diode (RTLED)^{1,2} has shown to offer attractive features when high speed and narrow linewidth are required and where coherent light is not obligatory. Indeed, the fast tunneling escape from the quantum well makes that the switch-off time is not limited by radiative recombination.³ Moreover, this device has a negative differential resistance (NDR) region and can have an even more pronounced decrease in optical output (quantum-well electroluminescence) in the same region² so that it can be used as an optical oscillator (e.g., an optical clock).

This optical oscillator can be made more useful if we provide a third contact to the device, so that a resonant tunneling transistor (RTT) is obtained. In recent years, several reports have discussed the RTT. Both the bipolar⁴ and the unipolar⁵ approach have been used for the realization of the quantum-well base layer. The unipolar RTT suffers from the fast intersubband relaxation to the first level which is filled with electrons for the high base-layer conductivity. This results in substantial base currents. The performance of the bipolar RTT on the other hand suffers from high scattering in the base due to the considerable quantum-well doping. In the tunneling transistors mentioned above, the base layer also forms the tunneling quantum well. Other authors have inserted a double-barrier tunneling structure in a traditional bipolar⁶ or unipolar⁷ transistor. The base layer is then a bulk layer and not a quantum well. The resonant tunneling hot electron transistor (RHET) is an example of this approach. A recent version⁸ however had a base layer of only 10 nm, which must be considered to be a quantum well.

In this work we use a base quantum-well layer⁹ adjacent to a tunneling structure. We prove that minority carriers can be injected from the base in the tunneling structure independently of a tunneling current between emitter and collector. This results in an optical output which is modulated by the base voltage. This resonant tunneling light emitting transistor (RTLET) is the transistor extension of the RTLED where the NDR in the emitter-collector characteristics are maintained due to the transparency of a quantum-well layer as base.

The transparency of the quantum-well base has al-

ready been discussed by Luryi.¹⁰ Electrons in a 2DEG are forced to reside at higher energies due to the Pauli principle. This results in incomplete screening of the emitter from the collector and hence in a semitransparent base. When the multiple energy levels of the quantum-well base layer are populated, the screening increases and a transistor with nontransparent base is obtained, leading to better electrical operation.

This implies that a relatively low base energy-level population allows us to maintain the emitter-collector current-voltage characteristics, including the NDR feature and the oscillation region. At the same time, we can use the quantum-well base layer to inject minority carriers into the tunneling structure.

The base transparency can be described quantitatively by a leverage factor of the base steering (λ_{BS}). It is defined as the relative change of the electrostatic potential (φ_{be}) to the change in Fermi potential (μ_{be}) with a constant emitter-collector bias (μ_{ec}):

$$\lambda_{BS} = \left. \frac{\partial \varphi_{be}}{\partial \mu_{be}} \right|_{\mu_{ec}} = \frac{C_Q}{C_{be} + C_{bc} + C_Q} \quad (1)$$

C_{be} and C_{bc} are, respectively, the emitter-base and collector-base geometric capacitances and C_Q is the quantum capacitance of the populated energy levels in the base layer. For a bulk base layer, C_Q approaches infinity and λ_{BS} reaches unity. For an almost empty lowest energy level C_Q and λ_{BS} approach zero, so that the influence of the base charge is low on the electric field over the structure.

This notion of C_Q is only valid when an equilibrium distribution function can be defined in the quantum well. This is possible when the quantum-well base layer is contacted. The influence of the energy-level linewidth must also be included to make the quantum-capacitance modeling more realistic.¹¹

We preferred a *p*-type tunneling structure with a *n*-type base layer because we can obtain good ohmic contacts on an ultrathin *n*-type layer using PdGe.¹² Moreover, electrons have a higher mobility in the base layer. On a *p*⁺-doped GaAs substrate, a collector layer, a base layer, a tunneling structure, and an emitter layer have been grown subsequently by molecular beam epitaxy (MBE). The collector layer consisted of a 1 μm GaAs *p*⁺ ($3 \times 10^{18} \text{ cm}^{-3}$) buffer layer and a 50 nm GaAs *p*⁻ ($1 \times 10^{16} \text{ cm}^{-3}$) layer.

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FIG. 1. Schematic band structure of the *pnp*-type device. Holes tunnel from the emitter to the collector. The base contact allows electron injection from the quantum-well base layer (InGaAs) into the tunneling structure.

The base layer consisted of a 10 nm GaAs n^+ ($1 \times 10^{18} \text{ cm}^{-3}$) layer, a 5 nm not-intentionally-doped (nid) GaAs layer, a 10 nm nid $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ base quantum-well layer, and a 10 nm nid GaAs spacer layer which after processing forms a passivation layer for the base.¹³ The spacer layer is partially consumed by the PdGe contact formation.¹⁴ The tunneling structure consisted of a 3 nm nid AlAs barrier, a 4 nm nid GaAs quantum well, a 3 nm nid AlAs barrier, and a 1 nm nid $\text{Al}_{0.08}\text{Ga}_{0.92}\text{As}$ launching layer.¹⁵ The emitter layer consisted of a 5 nm nid GaAs spacer layer, a 20 nm GaAs p^- ($2 \times 10^{16} \text{ cm}^{-3}$) layer, a 40 nm GaAs p ($4 \times 10^{17} \text{ cm}^{-3}$) layer, a 20 nm GaAs p^+ ($2 \times 10^{19} \text{ cm}^{-3}$) layer grown at low temperature¹⁶ (450 °C) to incorporate the high doping, and finally 65 nm MBE grown Al emitter contact metal.¹⁷ The Al metallization allows a thin emitter resulting in a lower absorption of the quantum-well light emission and a smaller base-surface exposure as a consequence of the underetch. The band diagram for the complete structure is schematically shown in Fig. 1. The launching layer increases the current peak-to-valley ratio (PVR) and decreases the tunneling through the first heavy-hole level. Fine tuning of this launching layer offers the opportunity for electron and light-hole resonance to occur at the same bias voltage.

$80 \times 80 \mu\text{m}^2$ squares in the Al metallization have been etched using $\text{HF} : \text{H}_2\text{O}$ (1 : 100) to form the emitter contact pads followed by a $120 \times 200 \mu\text{m}^2$ mesa etch in $\text{H}_2\text{SO}_4 : \text{H}_2\text{O}_2 : \text{H}_2\text{O}$ (1 : 8 : 800) in order to isolate the devices. The base etching is done using selective etchants ($\text{NH}_4\text{OH} : \text{H}_2\text{O}_2$ 1 : 100 for GaAs layers and HCl for AlAs layers) until below the lowest AlAs barrier. Then a PdGe metallization is done using the same photoresist mask. This results in a $90 \times 90 \mu\text{m}^2$ emitter area of which $1700 \mu\text{m}^2$ (the border) emits light. The base area is $12\,800 \mu\text{m}^2$. SEM photographs (not shown) prove that the self-aligned base etching and PdGe metallization restrict the free base path to less than 100 nm which is important for the free-surface recombination. The confinement of the base carriers in the InGaAs quantum well further restricts

FIG. 2. Common collector characteristics of the device at 77 K. The base voltage is varied between 0 and 1.5 V in four equidistant steps. Two regions can be distinguished. Below $V_E = 3.3$ V bipolar amplification occurs. For higher emitter voltages, inspection of the emitter and collector current shows a surplus in the emitter current coming from the base injection current. Consequently, the current PVR decreases.

the base surface recombination current. The PdGe contact metal has been annealed during 2' at 340 °C.

Figure 2 shows the common collector I - V characteristics of the device. If we compare the emitter current with the open base characteristic, we can clearly distinguish two areas. As long as the base doping layer is not completely depleted ($V_E < 3.3$ V), bipolar amplification occurs. The transistor acts like a bipolar transistor with a tunneling structure between emitter and base. The current gain is however low (10) and the device has no real applications in this voltage region. At higher emitter voltages, we find no bipolar amplification, but the injected base current is still observed and appears as a surplus in the emitter current. There are no electrons any more in the base doping layer, only in the quantum well and λ_{BS} decreases rapidly with increasing emitter voltage. The quantum-well base layer has a low influence on the field over the tunneling structure but still allows electron transport and injection in the tunneling structure. The NDR position is independent of the base voltage. A higher electron injection however decreases the PVR due to increased scattering.

Optical measurements were performed in a liquid-nitrogen cooled Dewar. Due to the dissipated power of the device, the temperature of the device is higher than 77 K. Measurements of the electroluminescence (EL) output of the device with the emitter bias in the NDR region (4V) at several base voltages, are shown in Fig. 3. The quantum-well electroluminescence (1.59 eV) clearly dominates the GaAs luminescence (1.43 eV), which indicates that the major part of the recombination takes place in the tunneling structure. This suggests that the device has a high quantum efficiency.² (The quantum efficiency is defined

FIG. 3. Optical output of the device biased in the NDR region ($V_E=4.0$ V). The base voltage is changed from 0.5 (low injection) to -0.5 V (high injection). The major part of the optical output comes from the recombination in the tunneling structure.

here as the number of photons for each electron injected from the base.) The optical output is directly modulated by the base voltage. A small Stark shift is only observed at large negative base voltages ($V_b = -0.5$ V). The influence of the emitter voltage on the Stark shift is much larger. The observed full width at half maximum (FWHM) of the quantum-well electroluminescence increases with electron injection due to the population of the electron energy level. The important light- and heavy-hole mixing produces the shoulder on the exciton line.¹⁸ Due to the band-gap narrowing of the $2 \times 10^{19} \text{ cm}^{-3}$ p -doped top layer (70 meV),¹⁹ the observed GaAs luminescence occurs at much lower energy than the intrinsic GaAs at 77 K. Only at very low voltages ($V_E = 1.8$ V) InGaAs electro-luminescence was observed (not shown), indicating that the tunneling holes have a low probability of being captured in the InGaAs base layer.

When an external emitter inductance (100 μH) is added, we obtain relaxation oscillations in the NDR region. An increase in base voltage from 0 to 2 V does not change the duty cycle. A change in the emitter voltage on the other hand alters the duty cycle significantly (11% for $V_E = 3.85$ V to 85% for $V_E = 4.2$ V) as it has been proven earlier for tunnel diodes.²⁰ This shows again that the base voltage does not significantly influence the field over the tunneling structure.

In this letter we have shown the possibility of injecting minority carriers into a resonant tunneling structure through a quantum-well base layer. The collector current does not change significantly with base voltage in the NDR region. The obtained optical output however is proportional to the applied base voltage, and is mainly consisted of quantum-well emission. Preliminary results on the oscillatory character of the device indicate that electro-optical heterodyne conversion can be obtained with this device.

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