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Fine structure of photoresponse spectra in a double-barrier resonant tunnelling diode

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Abstract. The photoresponsivity spectra of double-barrier resonant tunnelling diodes have been measured in a wide range of light wavelength as well as applied voltage. The complex behaviour of measured spectra is analysed, taking into account different channels for electron injection into the quantum well (QW). The results obtained yield evidence for modulated electron–hole (e–h) recombination in the QW provided by direct excitation of e–h pairs in the QW.

1. Introduction

Over the last decade resonant tunnelling diodes (RTDs) based on double-barrier heterostructures have attracted elevated attention due to their electronic and photonic applications. The latter were concentrated on utilization of the unique electronic and optic properties of these devices for lasers, detectors and modulators in the infrared to visible wavelength range [1, 2], and high-speed optically switched electronic devices [3, 4]. At the same time investigation of such devices under illumination could be successfully used for the understanding and analysis of basic electronic processes occurring in vertical transport devices.

This paper presents photoresponsivity measurements made as a function of excitation wavelength on a GaAs/AlAs double-barrier RTD. The results obtained at various bias voltages help to elucidate the relative contributions to the tunnel current from carriers directly injected into the well from the 3D emitter, versus those that tunnel in from an accumulation layer formed in front of the first barrier. Furthermore, they yield evidence for modulated electron–hole (e–h) recombination in the well provided by direct excitation of e–h pairs in the well.

2. Experiment

The RTDs we have studied were manufactured with the use of a GaAs/AlAs double-barrier heterostructure grown by molecular beam epitaxy (MBE) on an n$^+$-(100) GaAs substrate. The schematic layer structure of the RTD studied in this paper is shown in figure 1. The active part of it consists of a 4 nm thick GaAs quantum well (QW) with 2 nm thick AlAs barriers on both sides. These three layers were nominally undoped. A 100 nm thick undoped GaAs spacer layer was grown adjacent to the barrier on the substrate side and was separated from the substrate by a 100 nm thick highly doped ($\sim 10^{18}$ cm^{-3} Si) n$^+$-GaAs electrode region. A 100 nm thick GaAs top layer of similar doping was grown directly on top of the other barrier followed by a 0.5 μm thick heavily doped GaAs contact layer. The 16 × 16 μm^2 square devices were defined by wet-chemical mesa etching and Au/Ge/Ni alloyed ohmic contacts were fabricated on the substrate and on top of the mesa to provide measurements under applied bias.

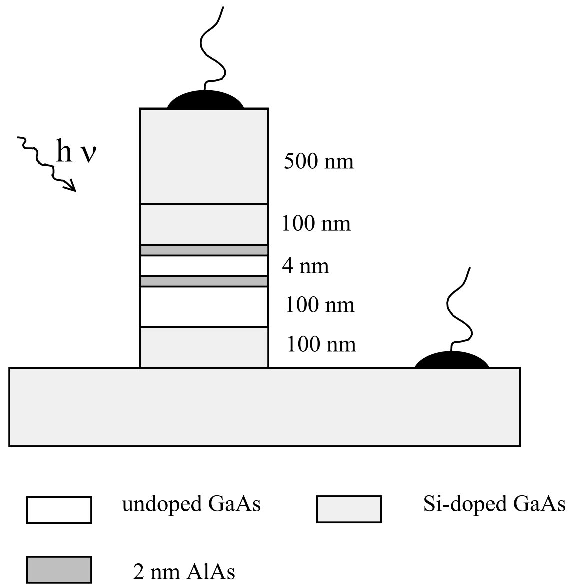

Figure 1. Schematic layer structure of the studied RTD.

The responsivity spectra of the RTD were measured using a standard spectral response system based on a 450 W xenon lamp and a grating monochromator. The bandwidth of the monochromatic light is 20 nm and the wavelength is changed in the 400–900 nm wavelength range in 10 nm steps. A calibrated single crystalline silicon detector is used for the system calibration, which gives the light intensity at each wavelength position. The xenon lamp light after the spectrometer falls on a semitransparent plate, where it is divided into two beams. The first one is guided to the monitor detector and measured as lock-in 1; the second one is guided to the Si reference detector and measured as lock-in 2. Exchanging the reference detector with the sample and comparing lock-in 1 and 2 values we can obtain the calibrated value of the signal. The RTD was illuminated by light incident at 45° on the side-wall facet. Taking into account light focusing by a lens and a real part of the beam that falls on the side-wall of the RTD with an incident optical power of 30 nW we obtain an irradiance of 0.043 mW cm^{-2}. With this value we did not observe visible changes in current–voltage (I–V) characteristics. Thus, the optically generated carriers did not significantly modify the potential distribution within the device.

3. Results and discussion

Typical responsivity spectra of the RTD, measured at 77 K and with different applied bias, are shown in figure 2. These spectra reveal a narrow band (labelled A in figure 2) at 1.5 eV and a broad band (labelled B in figure 2) at 1.65 eV with an extended short-wavelength tail. The intensities of both bands strongly depend on applied voltage and qualitatively follow the dark-current dependence of the I–V curve (figure 3). The I–V characteristics of the RTD measured in the dark reveals three resonant peaks under forward bias (figure 3), instead of the two peaks which actually appeared at reversed bias polarity. In all measurements the forward bias corresponds to a negatively biased substrate. Previously we suggested that the first two peaks observed for both bias polarities arise as a result of tunnelling of electrons injected from the 3D emitter through the first and second quasi-bound states of the QW, while the third peak observed at forward bias is stipulated by electrons injected from a 2D level in the accumulation layer formed in the front of the emitter barrier [5]. In the following we will concentrate on results obtained under forward bias.

In the band-to-band excitation case with energy close to the GaAs bandgap the e–h pairs are created throughout the structure outside the QW. The e–h pairs generated in the collector are shifted by the electric field. Electrons move towards the doped layer and recombine, thus do not contribute to the photocurrent, while the holes move to the collector barrier and are accumulated there. These carriers could tunnel throughout the double-barrier structure directly or overcome the barrier thermionically. The latter could be neglected due to the height of the barriers and the low temperature. The tunnelling holes recombine with electrons on the emitter side and thus contribute to the photocurrent. In contrast, the electrons photogenerated on the emitter side are injected into the QW. The magnitude of photoresponse increases with applied voltage under resonant conditions

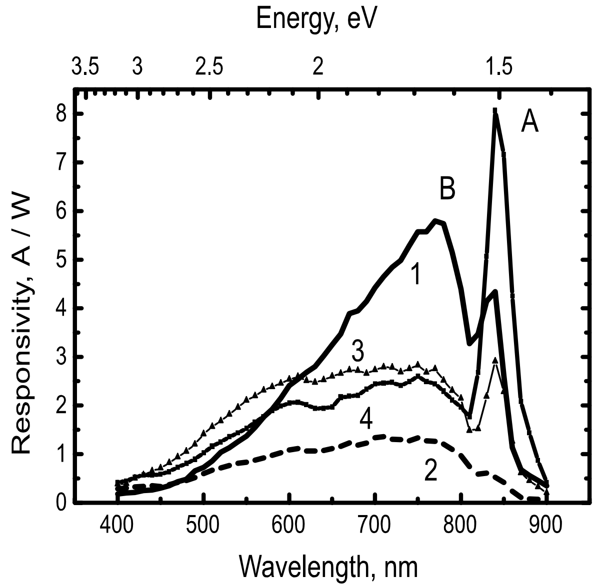

Figure 2. Photoresponsivity spectra measured at $T = 77$ K on the RTD biased at 1, 0.6; 2, 0.8; 3, 1.7; 4, 2.0 V.

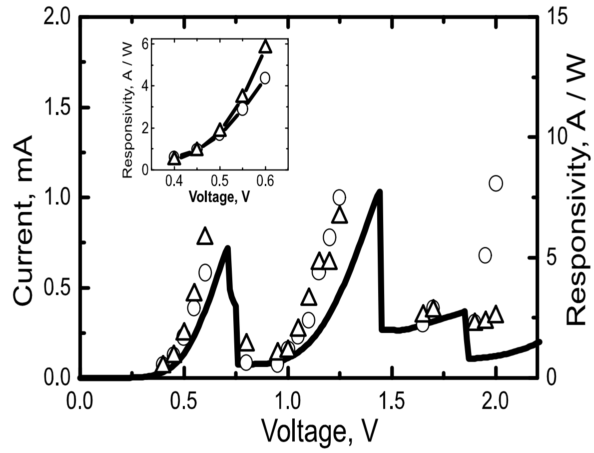

Figure 3. I–V characteristics of the RTD measured at $T = 77$ K under forward bias. Circles and triangles show the intensity of the photoresponse corresponding to maxima of the bands A (circles) and B (triangles). The dependence of these values within the first resonance is shown enlarged in the inset.

while it is low at biases corresponding to the resonance-off conditions. On the spectral dependence of the photoresponse the processes mentioned above should reveal themselves as a narrow asymmetric band with cut-off corresponding to the GaAs gap energy. This is because with increasing energy of the incident photons we should expect a sharp decrease of the photocurrent due to a high absorption coefficient and, consequently, a small number of photogenerated pairs. Surprisingly, a deep dip has been observed followed by a wide band, as seen in figure 2. The shape of the band is strongly affected by the applied voltage. There is a pronounced maximum at 1.65 eV followed by a short-wavelength tail within the first resonance, while the band becomes flatter with the centre of gravity shifted towards higher excitation energy within the second resonance and, finally, it almost vanishes at voltages corresponding to the passage of carriers above the barrier. Such behaviour of the spectral response could be explained with the following arguments. If the energy of the incident photons coincides with the energy difference between electronic and hole quasi-bound states in the QW, a direct generation of e–h pairs inside the QW is possible. The photocarriers are removed from the QW by the electric field remaining behind 'holes' which are filled immediately by electrically injected electrons from the emitter as well as holes from the accumulation layer adjacent to the collector barrier, thus giving rise to a photocurrent. Such a process should be efficient at resonance, while it is insignificant in the off-resonance regime because of a low probability of supplying carriers into the QW. This implies a strong field dependence of the photocurrent.

It is worth noting that there is an essential limitation of the photocurrent intensity related to the recombination of the photogenerated carriers. It was reported earlier [6] that a QW photoluminescence (PL) in double-barrier structures reveals field-dependent behaviour. Moreover, Vodjdani *et al* [7] have shown that radiative recombination does occur in the QW and roughly follows the current variation with bias, with the e–h pairs either electrically injected or photocreated directly in the QW. At the same time the PL dynamics directly reflects the source for holes participating in the recombination. The study of time-resolved PL from excitons in the QW shows that the net decay time of holes inside the QW is much shorter if the holes are created directly in the QW [8].

Now, it becomes clear why the peak intensity of band B (figure 3) grows more quickly than that of band A in the voltage region corresponding to the first resonance. Indeed, the QW luminescence is sublinear in the electron density and saturates at high electron injection. Taking into account the difference between the decay times for holes generated by different processes, we can conclude that saturation occurs at lower bias in the case of the e–h pair generation directly in the QW. The fact is confirmed by the $R_p^{A,B} = f(V)$ dependences plotted in the inset of figure 3. On the other hand, in the voltage region corresponding to the second resonance the recombination will be determined by the number of electrons that left resonance and relaxed onto the ground quasi-bound state of the QW. This amount, obviously, is smaller than is necessary for saturation and the $R_p^{A,B} = f(V)$ dependences almost coincide.

It should be noted that the spectral responsivity data obtained with illumination of the RTD in the wavelength range corresponding to interband transitions do not allow us to distinguish directly carriers injected into the QW from either 3D or 2D channels. Nevertheless, an explanation of the experimental results given above is more consistent with ballistic transport of tunnelling electrons.

An accumulation layer plays a more important role at high voltages and can be checked by photocurrent measurements. Indeed, the power of excitation used does not disturb a potential distribution along the device within the first and second resonances, while it stimulates visible changes of the I–V characteristics at bias exceeding 1.5 V, leading to a shift of the third peak position and variation of its magnitude. The character of the changes depends on the excitation energy. In most cases the excitation with photons whose energy corresponds to interband transitions caused a shift of the resonance towards higher voltage and, simultaneously, an increase of the current. In contrast,

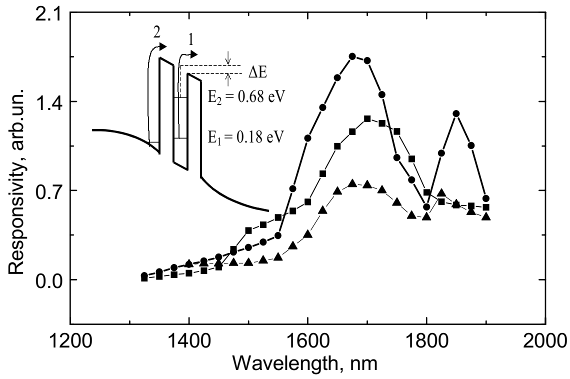

Figure 4. Spectra of the photoresponse measured at $T = 77$ K in the wavelength range from 1200 to 2000 nm. Solid circles, triangles and squares correspond to bias voltage of 0.7 V (squares), 1.1 V (triangles) and 2.25 V (circles). The inset shows the potential profile of the structure and the origin of excited carriers is marked by arrows.

intersubband excitation led to opposite changes. In figure 4 we plotted the responsivity of the RTD measured in the wavelength range from 1.3 to 1.9 μm. The spectral shape of the responsivity spectrum is essentially changed for different biases. The curve measured at 0.7 V shows an intense band at 1.73 μm. A shoulder on the short-wavelength side is also visible. At 2.25 V the curve is transformed into a two-band spectrum with an intense band at 1.67 μm and a weaker one at 1.83 μm. All these features we ascribe to photoinduced bound-to-continuum transitions. At low bias they correspond to excitation of electrons from a localized state in the accumulation layer (shoulder) and a ground quasi-bound state in the QW (band). In both cases the height of the barriers that could be overcome by the excited carriers is in good agreement with the potential profile calculated for the given structure. At high bias the energy needed for electrons to escape decreases due to lowering of the effective height of the barriers with increasing electric field. Moreover, the efficiency for electron excitation from the localized state in the accumulation layer grows considerably and the shoulder in the responsivity spectra transforms into a well pronounced band. It should be noted also that in off-resonance conditions the concentration of carriers stored in the accumulation layer is quite high and exceeds considerably the carrier concentration inside the well. This fact is confirmed by the spectral dependence measured at 1.1 V (figure 4). The excitation energy for both transitions non-monotonically depends on applied voltage. The voltage drop along the double-barrier part of the structure is small at resonance while it become considerable at off-resonance conditions, and lowering of the effective height of the barriers with increasing electric field should be taken into account. On the other hand the position of the quantum level in the accumulation layer will depend on both the applied voltage and the number of carriers stored ahead of the first barrier.

4. Summary

In conclusion, we have observed considerable transformation of the responsivity spectra in a double-barrier RTD resulting from a different origin of the photogenerated carriers. It has also been shown that the photoresponse in the infrared wavelength range could arise not only from the electrons excited inside the QW, but also from those localized in the accumulation layer. This fact should be taken into account when QW infrared photodetectors are designed.

Acknowledgment

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