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Fine structure of photoresponse spectra in double-barrier resonant tunneling diode

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Abstract. The photo-responsivity spectra of double-barrier resonant tunneling diodes have been measured in a wide range of light wavelength as well as applied voltage. The complex behaviour of measured spectra is analised 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.

Over the last decade resonant tunneling diodes based on double-barrier heterostructures attract an elevated attention due to their electronic and photonic applications. The latters 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 communication presents photo-responsivity measurements done as a function of excitation wavelength on a GaAs/AlAs double-barrier resonant tunneling diode. 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 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. The resonant tunneling diodes (RTDs) we have studied were manufactured with the use of a GaAs/AlAs double-barrier heterostructure grown by molecular beam epitaxy (MBE) on n^+-(100)GaAs substrate. Active part of RTD studied in this work 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 0.5-μm-thick heavy 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 substrate and on top of the mesa to provide measurements under applied bias.

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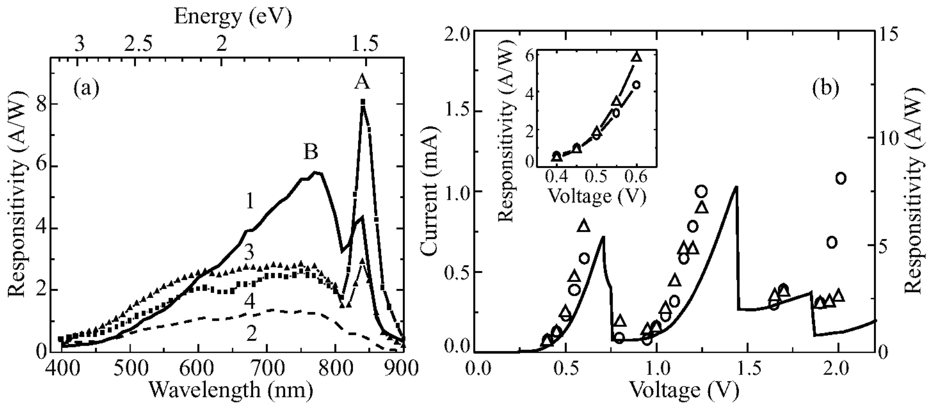

Fig. 1. (a) Photo-resposivity spectra measured at $T = 77$ K on the RTD biased at: 1—0.6 V, 2—0.8 V, 3—1.7 V, 4—2.0 V. (b) Current–voltage characteristics of the RTD measured at $T = 77$ K under forward bias. Solid circles and triangles show the intensity of the photo-response corresponding to maxima of the bands A (circles) and B (triangles). Enlarged dependence of these values within the first resonance is shown on inset.

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 to 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 RTD was illuminated by light incident at 45° on the side-wall facet. With an incident optical power of 30 nW, corresponding to an irradiance of 0.043 mW/cm^2 we did not observe visible changes in current–voltage characteristics. Thus, the optically generated carriers did not significantly modify the potential distribution within the device. Typical responsivity spectra of the RTD, measured at 77 K and with different applied bias, are shown in Fig. 1(a). These spectra reveal a narrow band (labeled A in Fig. 1(a)) at 1.5 eV and a broad band (labeled B in Fig. 1(a)) 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 (Fig. 1(b)). The current–voltage characteristics of the RTD measured in the dark reveals three resonant peaks under forward bias (Fig. 1(b)), 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 tunneling 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 further we will concentrate on results obtained under forward bias.

In the band-to-band excitation case with energy close to GaAs bandgap the $e{-}h$ pairs are creating 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 tunneling 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 photo-response increases with applied voltage under resonant conditions while it is low at biases corresponding to the resonance-off conditions. On the spectral dependence of the photo-response the processes conditions. On the spectral dependence of the photo-response the processes mentioned above should reveal itselves as narrow asymmetric band with cut-off corresponding to the GaAs gap energy. That 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, of a small amount of photogenerated pairs. Surprisingly, a deep dip has been observed followed by a wide band, as it is seen in Fig. 1(a). The shape of the band is strongly affected on the applied voltage. There is a pronounced maximum at 1.65 eV followed by short-wavelength tail within the first resonance, while the band becomes more flat with the center of gravity shifted towards higher excitation energy within the second resonance and, finally, it almost vanishes at voltages corresponding to passage of carriers above the barrier. The behaviour of the spectral response like that could be explained with the following arguments. If the energy of the incident photons coinsides 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 photo-carriers are removed out the QW by the electric field remaining behind holes which are filling 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 process should be efficient at resonance, while it is insignificant in the off-resonance regime because of a low probability to supply carriers into the QW. This implies a strong field dependence of the photocurrent.

It is worth to note there is an essential limitation of the photocurrent intensity related to the recombination of the photogenerated carriers. It has been reported earlier [6] that a QW photoluminescence (PL) in double barrier structures reveals field-dependent behaviour. Moreover, Vodjdani *et al.* [7] have shown the radiative recombination does occur in the QW and roughly follows the current variation with bias either the $e-h$ pairs 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 photoluminescence 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 the band B (Fig. 1(a)) grows more quickly that one of the band A under 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 a saturation occurs at lower bias in the case of the $e-h$ pairs generation directly in the QW. The fact is confirmed by the $R_p^{\mathrm{A,B}} = f(V)$ dependences plotted in the inset of Fig. 1(b). On the other hand, in the voltage region corresponding to the second resonance the recombination will be determined by the number of electrons which came out from the resonance and relaxed onto the ground quasi-bound state of the QW. This amount, obviously, is smaller than is necessary for a saturation and the $R_p^{\mathrm{A,B}} = f(V)$ dependences almost coinside.

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 to distinguish directly either carriers injected into the QW from 3D or 2D channels. Nevertheless, an explanation of the experimental results given above is more consistent with ballistic transport of tunneling electrons.

In conclusion, we have observed considerable transformation of the responsivity spectra in double-barrier resonant tunneling diode resulting on different origin of the photogenerated carriers.

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