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Photoresponse spectra in p–i–n diodes containing quantum dots

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Abstract
The photoresponsivity spectra of a p–i–n diode comprising of a layer of quantum dots (QD) in the intrinsic region are measured for a wide range of wavelengths of light and applied voltages. The complex behaviour of the measured spectra is analysed taking into account different channels for electron and hole capture onto the QD and their escape dynamics. The photocurrent data are accompanied by measurements of dark conductivity which reveal both S- and Z-shaped current bistability. The phenomena are explained in terms of a QD charging effect. A model presented in this work shows that switching between the two current states of the first and second bistable regions is controlled by the charges stored in the QD.

1. Introduction

p-i-n structures are well known as good photodetectors, because the length of the depletion region can easily be changed to obtain optimal quantum efficiency and a high speed of operation [1]. Absorption of light with energy $\hbar\omega \geqslant E_g$ in a semiconductor leads to the generation of electron–hole pairs. A pair created in the depletion region or at a distance equal to the diffusion length close to the depletion layer is separated by the electric field. As a result a current appears in the external circuit. For steady-state conditions and for small thermoactivated currents the photocurrent will be determined by a drift current of photocarriers generated in the i-region and by a diffusion current of photocarriers generated outside the depletion region. A double-barrier heterostructure placed in the i-region could significantly reduce the dark current due to a dominant contribution of the tunnelling recombination mechanisms to the current flow. The barriers would block the transfer of photogenerated carriers. Therefore, we should create a recombination channel for the carriers. Donor–acceptor pairs could be effective traps for injected carriers as they create levels in a semiconductor's bandgap and serve as recombination centres.

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In this work we investigate the spectral photoresponsivity of a GaAs p–i–n diode containing a plane of InAs quantum dots (QD) in an i-region as 'artificial impurities'.

2. Experiment

The p–i–n structure was grown by molecular beam epitaxy on an n^+-GaAs substrate. The structure includes two 3 nm AlAs barriers and a 6.2 nm GaAs quantum well (QW) in the undoped intrinsic (i) region. Undoped spacer layers of 100 nm (60 nm) separate the barriers from the 2×10^{16} cm^{-3} n-doped and the 2×10^{18} cm^{-3} p-doped contact layers. A 1.8 monolayer plane of InAs is embedded in the middle of the QW to form a plane of quantum dots (QD). The structure was grown at 600 °C except for the InAs layer and the overgrown GaAs cap layer, which were both grown at 450 °C to avoid indium segregation and desorption effects. A schematic diagram of the heterostructure is shown in figure 1. To carry out the two-terminal electrical measurements described in this paper, samples were processed as circular mesas of diameter 100–400 μm. Ohmic contacts were prepared with Au/Ge/Ni alloying on a substrate and the top layer of the heterostructure. Top contact metallization was ring-shaped allowing normal incidence photoexcitation of the sample.

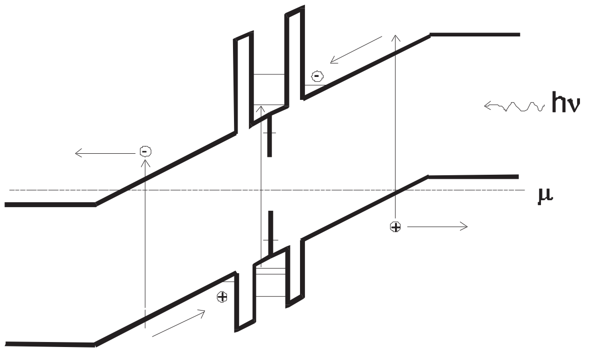

Figure 1. Schematic band diagram of the structure.

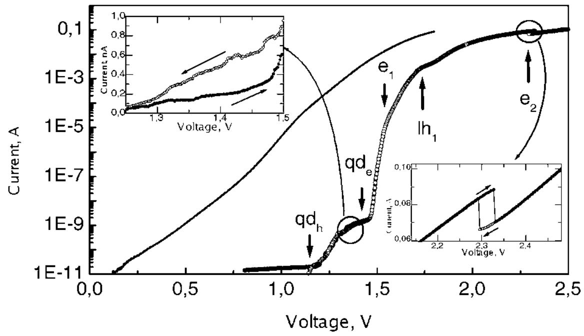

Figure 2. I–V characteristics of the double-barrier resonant-tunnelling structure measured at 4.2 K (circles) and 300 K (curves). Full (open) circles correspond to sweeping V up (down). Labelled arrows correspond to predicted resonances. The qd_h (qd_e) corresponds to the voltage at which the QD hole (electron) states begin to charge (discharge) under sweeping up (down). The first hysteresis loop, which exhibits inverted behaviour, is shown in upper inset. An enlarged picture of the second resonance is shown in the lower inset.

An analysis of low-temperature (30 mK–4.2 K) current–voltage (I–V) and capacitance–voltage (C–V) characteristics as well as photo- and electroluminescence spectra allows us to investigate mechanisms which are responsible for current formation in the structure and leads us to an estimation of the energetic parameters of the QD and QW electronic states.

3. Results and discussion

First we will concentrate on the dark current conductivity to elucidate the mechanisms which are responsible for current formation in the structure. Figure 2 is a helium temperature I–V curve of a 100 μm diameter structure taken during a voltage sweep from 0 to 2.5 V and back to 0 V. The arrows in the figure show the predicted positions of resonances through electron and hole quasibound levels in the GaAs QW. A pronounced hysteresis is displayed in the figure around a voltage of 2.3 V with the upper current line corresponding to the sweep from low to high bias. The observation of the hysteresis in the dc I–V curve is an indication of current bistability in the device. The negative differential resistance and the hysteresis displayed in figure 2 result from resonant tunnelling of electrons through the second quasibound level in the GaAs quantum well. Precise measurements also reveal another region of double-valued current behaviour at a voltage bias between 1.2 and 1.4 V. The feature becomes more visible with decreasing temperature. The upper inset in figure 2 represents the low-bias portion of the I–V curve measured at 30 mK. The lower current line corresponds to the sweep from a low to a high bias. The S-shaped bistable behaviour observed in this case is strongly related to the presence of QD states and is controlled by their net charge. To prove this statement we have to examine the processes that contribute to the current flow. At low temperatures and bias voltages far away from the flat band condition the main contribution to the current arises from hole and electron injection into the i-region and their sequential recombination. If the quasi-Fermi level in the positively biased side coincides with the lowest QD hole state hole tunnelling becomes possible. The arrows labelled in figure 2 mark the positions of the QD filling (qd_h) and the QD discharge (qd_e) of the holes in the voltage sweep. Therefore, the slowest process will restrict the current. The radiative recombination rate is typically of the order of 10^9 s^{-1} as measured by time-resolved photoluminescence experiments [2], while the estimated tunnelling rates for electrons and holes are significantly slower under the voltage range discussed. Moreover, in the beginning the hole tunnelling rate exceeds the electron one and the current is determined by the electron injection. With a further increase in bias voltage these rates invert and the hole injection rate becomes the dominant factor in the current restriction.

The double-valued behaviour of the current can be understood by considering different voltage distributions through the structure at the bias sweeps. Indeed, the electric field across the i-region is uniform until hole capture onto QD states becomes possible. Because of a low probability of recombination the current remains low and a positive charge accumulates in the QW. As a result, the electric field on the electron emitter side is smaller than the field on the hole emitter side. A further increase in the bias leads to an alignment of the quasi-Fermi level in the negatively biased side with the lowest QD electronic state. Electrons captured on QD states will neutralize the positive charge leading to the recovery of a uniform electric field distribution. The current also increases due to an enhanced electron–hole recombination. Thus, at the same bias two electric field configurations and, consequently, two current states should exist depending on the direction of the voltage sweep.

It should be noted that the magnitude of the effect depends on various parameters like tunnelling and emission rates for electrons and holes as well as electron–hole recombination rate and can be varied by altering the design of the structure or by external factors (for instance temperature). The temperature has no influence on the tunnelling process but changes the thermionic emission rates considerably which in turn causes changes in the conditions for bistability. This fact is confirmed by C–V measurement [3]. Additional evidence for the considerable contribution of the QD states to the observed bistability can be gained from measurements of I–V characteristics carried out on a similar device without the QD plane [4]. The authors of [4] did not observe any features like those discussed above. Thus, we suggest that S-shaped bistability can only occur in the presence of a QD plane.

The charging state of the QD also plays an important role in the formation of the second hysteresis loop. Indeed, for applied voltages greater than 2 V the holes injected from the p-doped contact layer may pass directly over the top of the second emitter barrier. This process reduces the number of holes entering the QW and also the filling of the QD hole states. At the same time electrons should be captured on the QD electron states resulting in a net negative charge accumulating in the QW. Thus, two electric field configurations are possible depending on the sweep direction, while the switch from the high-current state to the low one occurs at a higher voltage than the reverse switch.

For room temperature, as is shown in figure 2, the I–V peculiarities connected with resonant tunnelling are smeared. Nevertheless, we can reveal two exponential regions in the voltage range up to 1.2 V. In the range from 0.2 to 0.6 V the ideality factor equals 3 as for current limited by tunnelling processes, while in the range from 0.6 to 1.2 V the ideality factor reduces to 1.6 as for current limited by recombination processes [5].

The zero-bias spectral photoresponse of the diode, measured within the range from 1 to 2.5 eV, reveals a complex behaviour. The edge of the photoresponse corresponds to an energy of 1.42 eV which coincides with a GaAs bandgap at room temperature. Taking the absorption coefficient for this wavelength into account we can consider that electron–hole pairs are generated in both electron and hole contacts. Consequently, electrons (holes) accumulate in front of the barrier on the hole (electron) emitter side. The AlAs barriers block direct drift of the photogenerated carriers. Indirect recombination of electrons and holes stored outside the double barrier structure also has a low probability due to their spatial separation. At the same time extension of the wavefunctions of the QD states considerably enhances the probability for capture of photogenerated carriers by the dots. Thus, the high responsivity observed at zero bias can be explained by recombination of photogenerated carriers via the QD states. With an increase in the photon energy one can see a sharp maximum in the photoresponse spectrum at an energy of 1.48 eV and a maximum at 1.59 eV with a broad high-energy tail (figure 3). The first and second maxima are in good agreement with the transition energy from the ground state of heavy and light holes to the ground electronic state in QW. Here we consider a lowering of the ground electron energy level due to a perturbation caused by the presence of a thin InAs layer. The magnitude of the photoresponse is evidence of the high spectral photosensitivity of the diode. The dependence of the quantum efficiency on the applied voltage at a photon energy of 1.59 eV has a non-monotonic behaviour. The quantum efficiency decreases with increasing positive bias and reaches a minimum at +0.6 V, whereas the increase of efficiency with decreasing negative bias is observed as shown in figure 3. This gives direct evidence that the device is operating in the photovoltaic mode.

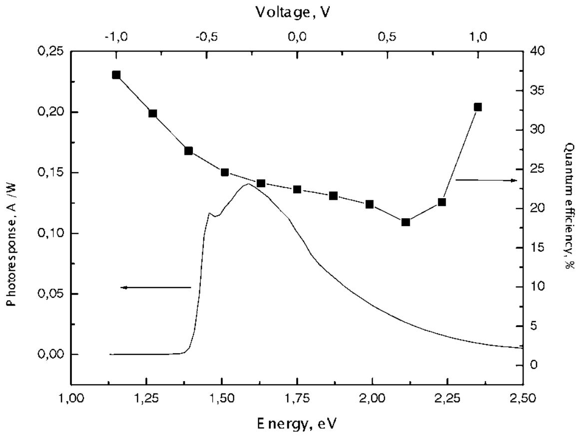

Figure 3. Left and bottom scale: spectral photoresponse dependence at zero bias measured at 300 K. Top and right scale: quantum efficiency as a function of applied voltage at a radiation energy of 1.5897 eV.

4. Conclusions

We have investigated the influence of an InAs QD layer in the intrinsic region of a p–i–n diode on the photoresponse spectra of the structure. The results show the efficiency of this design for the fabrication of sensitive multiband photodetectors. The photoresponse data are supported by dark conductivity measurements made to investigate the mechanisms of diode current formation. Two kinds of current bistability are observed. The first hysteresis loop appears in the I–V curve at biases below flat-band conditions. The hysteresis exhibits inverted behaviour as compared with the second unstable region that is revealed at biases above the flat-band regime. It is shown that switching between the two current states within the first as well as the second bistable regions is controlled by the charges stored in the QD.

Acknowledgments

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