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Capacitance–voltage characteristic as a trace of the exciton evolvement from spatially direct to indirect in quantum wells

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Abstract
We have investigated the photo-excited capacitance–voltage (C–V) characteristics as well as the photoluminescence spectra under different biases of a wide quantum well (QW) embedded in an n^+–i–n^+ double-barrier structure. The pronounced peak feature at zero bias in the C–V spectrum observed upon illumination is regarded as a kind of quantum capacitance related to the quantum confined Stark effect, originating from the spatial separation of the photo-generated electron and hole gas in the QW. This fact is further demonstrated through the comparison between the C–V curve with the PL intensity versus applied voltage relationship under the same excitation. The results may provide us with a more direct and sensitive means in the detection of the separation and accumulation of both types of free carriers—electrons and holes—in low-dimensional semiconductor structures, especially in a new type of optical memory cell.

1. Introduction

Low-dimensional semiconductor heterostructures have attracted much attention of researchers since their capability of restricting the motion of carriers due to size quantization generated a new set of physics as well as devices. It has been well known that the capacitance characteristics of such systems are of basic importance both in fundamental research and in device applications. The capacitance measurements in a semiconductor heterostructure show some particular characteristics that are related to the carrier confinements, which can give useful information on the structural and electronic properties such as the concentration and distribution of carriers [1, 2], density of states [3–5] and band offsets [6]. Capacitance knowledge is also essential in incorporating semiconductor heterostructures into practical applications such as high-speed electronic and optoelectronic devices because it has a significant effect on the maximum operating frequency obtainable [7–9]. Recently, several groups have used the C–V measurement in combination with an optical excitation to access information about photo-generated carriers' accumulation in MISFET structures with quantum dot layers embedded [10–12].

In this work, we will show how the traditional C–V measurement can be utilized to an optically excited quantum well (QW) to trace the exciton evolvement with applied biases. We observed a pronounced peak around zero bias in the C–V spectrum upon rather weak illumination, strengthened and broadened with increasing exciting power. Such a capacitance feature reflects directly the spatial separation process of the photo-generated electron and hole gas in the QW as the applied bias increases and is referred to as the QCSE-related quantum capacitance [13]. Comparison between the C–V characteristic and the fitted PL intensity as a function of applied voltage gives further support for the above claim. Being different from former work, here in our case, C–V measurements revealed the unique feature

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corresponding to the separation and accumulation of both types of free carriers—electrons and holes—in two-dimensional semiconductor structures.

2. Experimental details

The sample under investigation is a symmetric n^+–i–n^+ double-barrier structure (DBS) grown by molecular beam epitaxy (MBE) on a (100) oriented n^+-GaAs substrate. The central part, consisting of two 25 nm-thick undoped AlAs barriers and a 63.5 nm-thick undoped GaAs well in between, is separated from either the 2 μm-thick GaAs buffer layer (Si-doped to 10^{18} cm^{-3}) or the 100 nm-thick GaAs cap layer (Si-doped to 10^{18} cm^{-3}) by a 50 nm-thick undoped GaAs spacer. By using standard photolithography the wafer was etched into rectangular mesas (650×350 μm^2) and separate ohmic contacts were established on their top and back contact layers. The top contact was fabricated by evaporating and subsequently alloying a rectangular Au/Ge/Ni contact pattern onto the cap layer with a square aperture (300 μm) left for the optical access. The back contact was formed by alloying In to the n^+-GaAs substrate.

For the experiment the sample was mounted on the cold finger of a variable-temperature ($10 \sim 300$ K) CCS-300 closed cycle refrigerator system and the temperature was kept at 10 K. For photo-excitation a He–Ne laser beam was focused onto the aperture region of the sample. The C–V characteristics were recorded at a frequency of 1 MHz using a Hewlett-Packard 4284A LCR meter and the amplitude of the modulation signal was chosen to be 10 mV. The PL measurements were performed on a Dilor Super-Labram system with a liquid-nitrogen-cooled CCD detector.

3. Results and discussion

3.1. Photo-excited C–V characteristic and its physical mechanism

The measured capacitance as a function of bias voltage of the DBS under dark conditions or upon He–Ne laser excitation with different powers is presented in figure 1. Low excitation density ensured high-precision measurement free of nonlinear effects. A sharp peak at zero bias features the photo-excited curve and it is strengthened and broadened with increasing excitation density. To give a reasonable explanation, we start from the definition of the DBS capacitance.

Considering the employment of nontransparent thick barriers in the DBS, the parallel-plate geometry is applicable for its modelling [2, 13]. Thus the capacitance of the DBS can be defined as $\mathrm{d}Q_s/\mathrm{d}V$, where Q_s denotes the sheet density of net charge dwelling in either the accumulation region or the depletion region and V the voltage drop across the DBS.

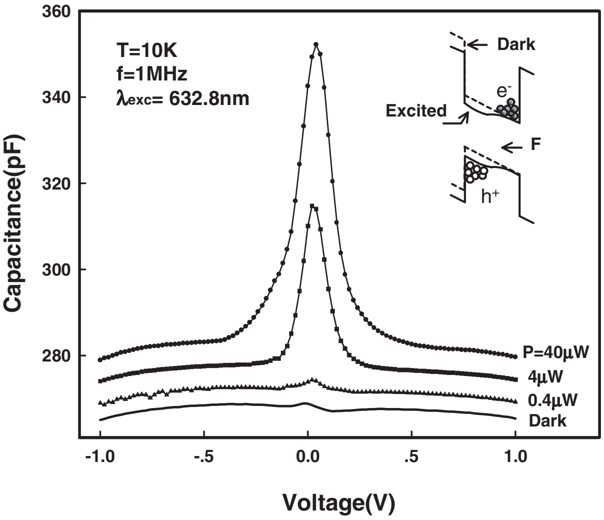

Figure 1. Measured capacitance as a function of the bias voltage applied on the DBS upon He–Ne laser excitation of different powers at 10 K. The amplitude and frequency of the modulation voltage are $\mathrm{d}V = 10$ mV and $f = 1$ MHz, respectively. The vertical scale refers to the bottom trace ('Dark'), and a constant offset (5 pF) is added to the other traces for clarity. The inset shows the band profile of the QW under electric field. Upon excitation there is a reduction in the voltage drop across the QW due to the band-bending effect caused by the spatial separation of the photo-excited electron and hole gas.

Under dark conditions, there must be no free-carrier accumulating in the central well so that it acts as an insulator. As for what is expected for the relatively small bias range, there is no distinct feature in the dark C–V spectrum (the solid curve in figure 1) except a slight decrease with applied bias owing to the depletion layer capacitance. When a He–Ne laser illumination is continuously shone on the structure, a certain number of electron–hole pairs will be injected into the QW. Since the electron and hole relaxation rate should be much larger than the recombination rate, the electrons and holes inside the QW can then be considered in quasi-equilibrium states respectively. At zero bias, these carriers distribute symmetrically in the well as decided by their corresponding wavefunction features. With increasing bias either positively (surface contact is positively biased) or negatively, the electron and hole envelope wavefunctions are shifting in opposite directions toward their respective potential minima. As a result, the electrons and holes are partially separated in space, which in turn gives rise to a 'depolarization' field opposite to the external field and induces band bending in the central well region (see figure 1 inset). In this case, to raise the voltage drop across the DBS by a certain amount $\mathrm{d}V$, which must be accompanied by a further polarization of electrons and holes, a larger amount of charge increment $\mathrm{d}Q_s$ should be required compared with that under dark conditions. For a wide QW as in our case, a rather weak field can induce strong deformation of the rectangular potential well and accordingly a drastic charge separation takes place, which would account for a great increase in the capacitance of the DBS under small biases when optically excited. With further increasing bias, the relative shift of electron and hole wavefunctions slows down and eventually saturates, and the capacitance correspondingly declines to its dark value. That is why we observed a sharp peak around zero bias in the photo-excited C–V spectrum. As this capacitance characteristic directly reflects the variation in the overlap between electron and hole wavefunctions with applied voltage, it is referred to the QCSE-related quantum capacitance [13].

According to the above analysis, one can easily understand the strengthening and broadening of the capacitance peak with excitation power. A higher exciting power results in a

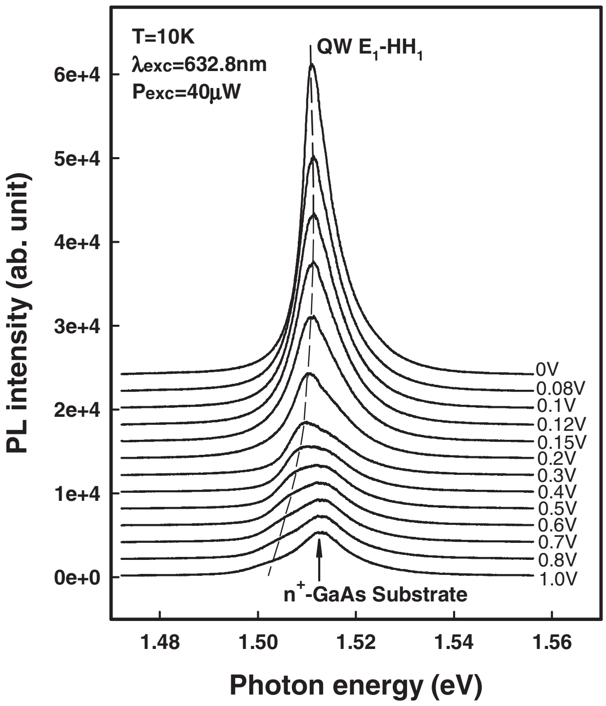

Figure 2. The PL spectra of the sample measured at different applied biases at 10 K. A He–Ne laser at a power of 40 μW was used for excitation. The dashed curve traces the Stark red-shift of the QW luminescence.

larger number of photo-generated carriers and correspondingly a stronger screening effect originating from the spatially separated electrons and holes (for detailed theoretical modelling see our former work [13]).

3.2. *Photoluminescence spectra under different biases*

In figure 2, we presented the steady-state PL spectra for several positive biases with an exciting power of 40 μW, those for negative biases exhibit similar behaviours and are not shown here. The main peak traced by the dashed curve, which experiences the Stark red-shift as well as a tremendous intensity reduction with applied bias, is believed to come from the E_1–HH_1 transition in the 63.5 nm-thick wide QW. A broad background feature superimposing on the main peak, becoming more obvious and eventually dominating the PL spectra with increasing bias, is assigned to the luminescence of the heavily doped GaAs substrate, whose peak position and intensity change little with biases.

3.3. *Comparison between the C–V and PL intensity versus V relationships*

After fitting the PL spectra with two Lorentzian line shapes, we plotted the integrated intensity of the QW luminescence as a function of applied voltage in figure 3(*a*). For comparison, the C–V spectrum under the same excitation has also been shown in figure 3(*b*). As is a well known fact, the fast decreasing and even quenching of the QW's PL intensity with increasing voltage either positively or negatively exhibits one usual piece of experimental evidence for the QCSE, since the relative separation of the electron and hole wavefunction results in decreasing dipole matrix elements for the E_1–HH_1 transition. In the C–V spectrum we find that the photo-capacitance response declines almost synchronously. Thus we are further convinced that here the C–V measurement just traces the exciton evolvement from spatially direct to indirect with applied biases. In a sense, this kind of electrical test is more straightforward and more sensitive than the often used optical spectroscopies.

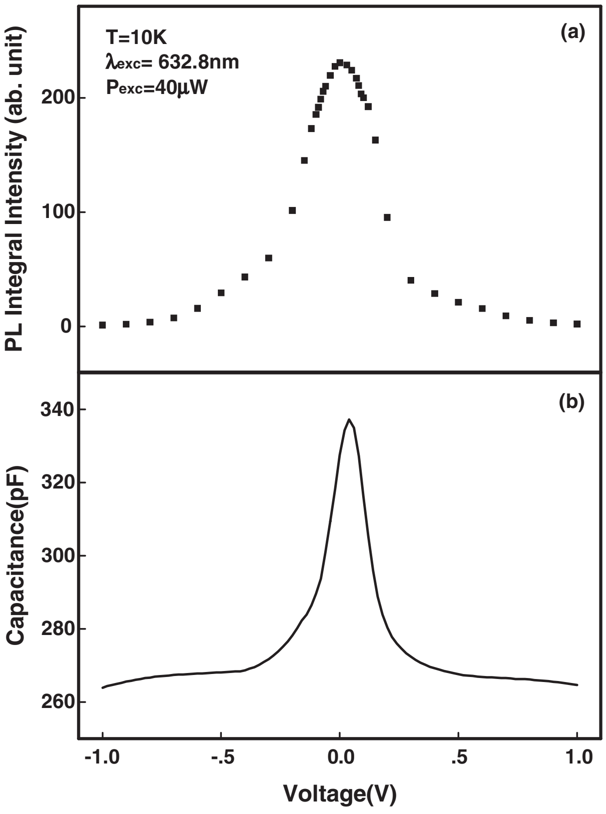

Figure 3. (*a*) Integrated intensity of the QW luminescence as a function of the applied bias with 40 μW He–Ne laser excitation; (*b*) C–V characteristic with the same excitation.

4. Conclusions and prospects

We have studied the photo-excited C–V characteristics of a wide QW. The main feature, a sharp peak at zero bias, is a direct reflection of the charging process owing to the spatial separation of the photo-generated electron and hole gas under applied biases, and is considered as the QCSE-related quantum capacitance. PL spectra of the QW under different biases have also been utilized to provide additional support for the above point of view.

Recently there has emerged a new type of optical memory cell. In such a cell, light energy can be converted into spatially separated electron–hole pairs under certain bias conditions and can be locally accumulated and stored. At a chosen moment, the light can be re-emitted from the cell in a short and intense flash. The radiative recombination lifetime of photogenerated electron–hole pairs can be voltage-tuned over many orders of magnitude with the upper limit determined by the cell structure [14, 15]. We hope that applications of this photo-excited C–V technique in future investigations of such kinds of device could bring us a deeper insight into the physical mechanisms embedded and provide us better operation guides.

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