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Electric field effect in the spin dynamics of self-assembled InAs/GaAs quantum dots

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Abstract

We identify fundamental mechanisms of electron and hole dynamics in self-organized InAs/GaAs quantum dots (QDs) subject to vertical electric fields by photocurrent investigations. We propose a spin–flip mechanism involving a spin exchange between neighboring QDs. The spin–flip process is revealed in the photocurrent dynamics when the exciton population increases unexpectedly with reverse bias.

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1. Introduction

Self-assembled quantum dot (QD) structures are potentially promising for memories due to the large confinement energy for holes. The spin of an electron or a hole in such structures is very important in determining their electronic and optical properties. Its manipulation has great potential in spintronics and quantum information processing [1–3]. One of the most intensively studied self-assembled QD systems is the InAs/GaAs system. Experimental evidence of a dynamical process of dots charging and discharging with photogenerated holes and electrons revealed by the photocurrent measurements under illumination is presented and discussed.

Experimental results allow us to verify the influence of an electric field and of charging effects on excitons optically excited in a self-assembled QD. Photocurrent spectroscopy is a suitable technique to investigate the absorption of a QD, which can give information on the mechanisms of capture and escape [4]. Tunneling carrier escape has been detected and confirmed in InAs QDs [5–7].

We report here a novel process that offers control over the conversion of dark into bright excitons in a QD. An electron spin is exchanged with a spin in an adjacent QD by a coherent Kondo-like tunneling interaction. Dark excitons have shown long lifetimes, which are attractive for applications, but it is still a challenge to manipulate dark excitons in a controlled way. It is pointed out that a spin–flip mechanism can occur in a controlled fashion in self-assembled QDs, and we present a qualitative model that explains the observed behavior through photocurrent results.

2. Experiment

The sample studied was a GaAs p–I–n diode structure grown by molecular-beam epitaxy at 500 °C with five layers of InAs dots separated by 20 nm of undoped GaAs. The dots were formed from 2.4 ML of InAs deposited at 0.39 ML/s using Stranski–Krastanow technique, and had a density of about $5 \times 10^{10}\,\mathrm{cm}^{-2}$. The electric field F across the intrinsic region is controlled by the built-in potential

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(U_b) and the applied bias (U). Mesas with 400 μm were employed.

The samples were mounted in a variable temperature cryostat coupled with the measurement system. The samples are excited with energy of 1.94 eV by a HeNe laser. For this energy, the electron–hole pairs are excited into higher QD levels. For the PL measurements, the emitted light was dispersed by a 0.8 m spectrometer and detected by a liquid-nitrogen-cooled Ge detector using standard lock-in technique. For the photocurrent measurements, a micro-PL set-up was used to excite the mesas. Since only the QDs in the contact region significantly contribute to the PC signal, it was possible to chop the laser beam and to measure the modulated signal with a lock-in amplifier.

3. Experimental results and discussions

At low temperatures, escape from the dots occurs by tunneling. By varying the electric field we control the tunneling rate and we are able to observe its competition with relaxation and recombination. Fig. 1a shows the PL spectrum of the corresponding InAs/GaAs QD structure. In Fig. 1b and c, the variations of the intensities of the PL and PC are plotted against applied voltage (U) at low temperature ($T = 10$ K). The PC intensity shows the inverse dependence compared to the PL, providing evidence for competition between tunneling and radiative recombination. Thermal escape out of the QD is negligible with respect to the tunneling escape due to the low temperature [8].

Fig. 1b displays the field dependence of the PL intensity at different detection energies (1–4). It was obtained using excitation at 1.94 eV from a HeNe laser. Both PL × U and PC × U show a pronounced shoulder at $U = -1.177$ V. The shoulder is significantly more pronounced when detected on the low-energy side of the QD emission, i.e., on large dots. In fact, this behavior will be associated with the spin–flip mechanism. The value of the reverse bias with the onset of saturation of the PC signal coincides with the value of the bias where the shoulder is observed on the PL intensity. PC is complementary to PL since it detects those excitons that are excited in the dots and then escape by tunneling. So, a very good anticorrelation between the two processes is observed in Fig. 1, showing that tunnel escape dominates the PL quenching.

By adjusting the bias applied between the n and p contact layers, we control the electron occupation of the dots. In a p–i–n diode, the tunneling times for electrons and holes are obtained considering $F = F_0 + \Delta F$, where $F_0 = (U_b - U)/d$ and $\Delta F = (n_h - n_e)eN_{QD}/\varepsilon_0\varepsilon_r$. The electric field F across the intrinsic region is controlled by the build-in potential (U_b)~1.5 V and the applied bias (U) and d is the width of the intrinsic region. At low electric fields, the holes as well as the electrons stay in the QD and recombine. Charge accumulation caused by tunneling of optical carriers can be excluded. At high reverse bias, the internal

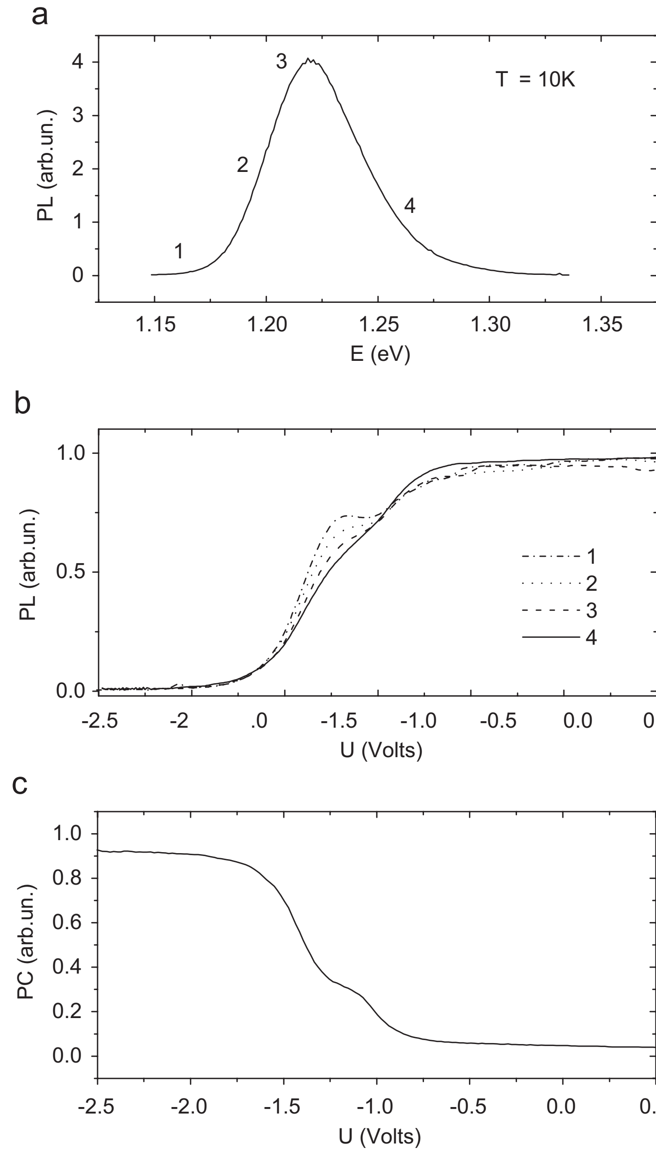

Fig. 1. (a) PL spectrum of an InAs/GaAs self-assembled quantum dot (b) PL intensity at different detection energies, and (c) Photocurrent signal as a function of the applied voltage U. The excitation energy was maintained constant at $E_{ex} = 1.94$ eV, and the power density was 6 W/cm^2.

electric field is strong enough to separate the optically excited excitons. The electrons as well as the holes tunnel out of the QDs at different rates. In a previous work, as the reverse bias is increased between −2 and −6 V, the photocurrent behavior demonstrates that carriers can only tunnel out from the dots for $U < -2$ V; for $U > -2$ V, they relax to the ground state and recombine [4].

Fig. 2 shows the PL intensity as a function of energy for different applied voltages. It is clear that the strongest change with voltage occurs at high energies, which demonstrates the dependence of carrier tunneling on the QD emission energy. Tunneling escape produces changes in the PL intensity due to the promotion of photoexcited excitons towards smaller or bigger dots around the average size distribution. The probability of tunneling and escape