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Inter-dot electron transport in coupled InAs quantum dots under a magnetic field

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Abstract
We studied electrical transport properties of coupled InAs quantum dots (QDs) embedded in GaAs. A resonance peak in the current–voltage characteristics was observed in the low temperature region. When the magnetic field was applied, a linear shift of the resonance voltage was observed. As a result of the g-factor estimation, the resonance is attributed to the current corresponding to the electron transport through coupled InAs QDs.

1. Introduction

There have been many works dealing with self-assembled quantum dot (QD) systems. The interest in such systems comes from the fact that we can clearly observe quantum confinement effects for electrons located on each dot. In addition, there is attractive merit in this dot system, when the dot density can be increased to a very high value, and the spacing between QDs can be decreased small enough to cause inter-dot coupling of electron wavefunctions. Such electronic coupling is expected to show interesting phenomena, for example, the magnetic ordered state can be achieved in the coupled QD system composed of non-magnetic semiconductor materials [1]. There are many other works which treat the inter-dot electric couplings [2, 3]. Since the electron state can be easily controlled, by applying a gate electrode for instance, such structure will open new device applications. Previously, we reported photoluminescence (PL) from high dot density samples indicating asymmetry in the PL spectra due to the inter-dot electric coupling [4]. In this paper, we prepared InAs/GaAs self-assembled QD samples having different dot densities. We measured photocurrent properties for these samples in order to investigate the existence of inter-dot electronic coupling in the electron transport.

2. Experiments

A single layer of self-assembled InAs QDs was grown on top of a 20 nm undoped GaAs layer by Stranski–Krastonov mode, and was capped by a further 10 nm undoped GaAs layer by using molecular beam epitaxy (MBE). The dot density was varied by changing the In flux without rotating the substrate in the MBE growth procedure. We prepared two types of samples having different QD density. One has 1.8×10^{11} cm^{-2} QD density with 4 nm mean distance from a QD to its nearest neighbour, and the other has 5.0×10^{10} cm^{-2} QD density with 8 nm mean distance. These mean distances were obtained from atomic force microscope observation. After the MBE growth, AuGeNi source-drain electrodes of 200 μm × 150 μm area with 10 μm spacing between them were formed on the GaAs cap layer. The in-plane lateral current–voltage (I–V) characteristics were measured at 1.6–192 K under the illumination of a cw He–Ne laser light to provide carrier electrons. A magnetic field was applied along the direction perpendicular to the QD plane.

3. Results and discussion

Figure 1 shows I–V characteristics measured at 1.6 K. In differential conductance, which is shown in the inset of figure 1, we can clearly see resonance peaks for the higher dot

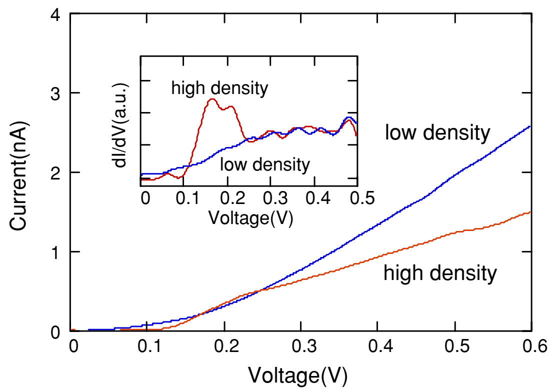

Figure 1. Photoconductance and differential photoconductance (inset) as a function of applied voltage.

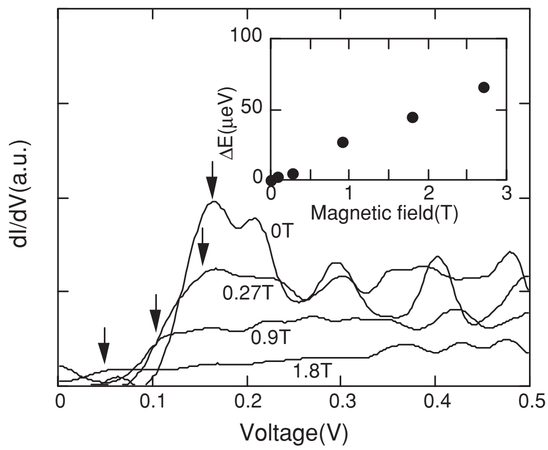

Figure 2. Differential photoconductance for the higher dot density sample under different magnetic fields. Inset: the energy difference versus applied magnetic field.

density sample. On the other hand, there are no such peaks in the case of the lower dot density sample. We measured the temperature dependence of the I–V characteristics and found the peak clearly seen in the higher dot density up to about 50 K, which corresponds to the temperature dependence of the asymmetry in the PL spectrum caused by inter-dot electric coupling [4]. In addition, the mean inter-dot transfer energy of the higher dot density sample was estimated to be larger, by two orders of magnitude, than that of the lower dot density sample. Thus, the peaks observed in the I–V characteristics are attributed to the resonant tunnelling of adjacent QDs. Resonant tunnelling through linear arrays of QDs has been discussed theoretically [5]. In our experimental conditions, since the resistance for the current flowing through the in-plane QD layer is very high, we are in the Coulomb blockade regime. The spectrum for the tunnelling current basically has the spectral shape of a Lorentzian function.

Figure 2 shows typical I–V characteristics for the higher dot density sample under different magnetic fields. As the magnetic field is increased, the onset peak position indicated by arrows shifts to the lower voltage side, while they do not exist in the lower dot density sample. When the magnetic field is applied, a spin split of the ground state of QD occurs due to the Zeeman effect, the splitting increases with increasing magnetic field as written for the energy difference ΔE as $\Delta E = g\mu_B B$, where g is the g factor of the QD systems. Assuming that the electric field between each QD is uniform in this system, ΔE value can be expressed by the linear function with respect to the applied magnetic field B (see the inset of figure 2). The absolute value of the g factor thus was 0.01. Thornton *et al* [6] reported a similar small value of the g factor of InAs QD embedded in AlAs. In addition, Snelling *et al* [7] reported that the sign of the g factor in GaAs/AlGaAs quantum well changes from negative to positive as the well width is reduced. The magnitude of the g factor of the III–V semiconductors can be estimated by using a simple three-band model. Hermann and Weisbuch [8] reported that the value of the g factor is given by

$$\frac{g}{g_0} - 1 = -\frac{P^2}{3}\left(\frac{1}{E_0} - \frac{1}{E_0 + \Delta}\right), \qquad (1)$$

where $g_0 = 2$, $P^2 = 22.2$ eV is the momentum matrix element for InAs, $\Delta = 0.38$ eV is the valence band spin–orbit split-off gap for InAs and E_0 is the bandgap. According to equation (1), the g factor value for the bulk InAs material is estimated to be −14.8. In contrast to this value, the absolute value of the g factor decreases in the QD systems, because the optical gap energy E_0 in QDs is much larger than the bulk gap energy. The gap energy E_0 in the present QD system is 1.32 eV. Using this value we can estimate the g factor value to be −0.51. Thus, the experimentally obtained g factor value agrees with the theoretically estimated values. Therefore, we can conclude that the observed resonance feature in the I–V characteristics stems from the electron transport through the spin-split state in InAs QDs.

4. Conclusion

We studied electron transport properties of coupled InAs QDs embedded in GaAs. The resonance peak in the I–V characteristics was observed in the low temperature region. The dependence of the resonance voltage on the magnetic field indicates that the resonance was attributed to the current corresponding to the electron transport through QDs. The present results indicate that this QD system is one of the candidates to realize an electrically coupled system and has a possibility of producing a novel field of fundamental physics as well as device applications.

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