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2007 J. Phys.: Condens. Matter 19 506207

(http://iopscience.iop.org/0953-8984/19/50/506207)

IOP Publishing Journal of Physics: Condensed Matter

J. Phys.: Condens. Matter **19** (2007) 506207 (7pp) doi:10.1088/0953-8984/19/50/506207

Transport hysteresis in AlGaAs/GaAs double quantum well systems with InAs quantum dots

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Received 10 August 2007, in final form 18 September 2007
Published 19 November 2007
Online at stacks.iop.org/JPhysCM/19/506207

Abstract
We report on the charge storage effect of InAs quantum dots (QDs) embedded in the upper well of the AlGaAs/GaAs double quantum well structure. Zero field longitudinal resistivity and Hall resistance at weak magnetic fields exhibited a hysteresis effect during the sweeping of the gate voltage due to the accumulation of charges in the quantum dots. On reverse sweeping the gate voltage, the accumulated charges are prevented from being rapidly depleted due to the screening effect of the upper two-dimensional electron gas, which could significantly enhance the operation and reliability of QD-based non-volatile memory devices.

1. Introduction

Self-assembled InAs quantum dots have attracted much attention due to their potential applications in fabricating ultra-dense storage memory devices based on their charge storage effect. The amount of charge that can be stored in a quantum dot (QD) is determined by a self-limiting process governed by the Coulomb blockade effect and therefore only a well defined number of electrons can be accommodated in each QD at a particular gate voltage. In this scenario, the storage capacity of QD-based memory devices depends primarily on the density of the QDs and is totally independent of the size of the dots [1]. The zero-dimensional sub-bands of the QDs trap the charges that are created by electrical or optical excitation under suitable biasing conditions [2, 3]. For instance, in the case of optical read write memory devices, a pronounced hysteresis effect is observed when the QDs are illuminated with laser light due to the trapping of the charges into the QDs. The trapped charges are then depleted by applying negative bias to the gate. Similar studies were carried out for QDs grown in the vicinity of a two-dimensional electron gas (2DEG). The hysteresis effect was investigated by observing the

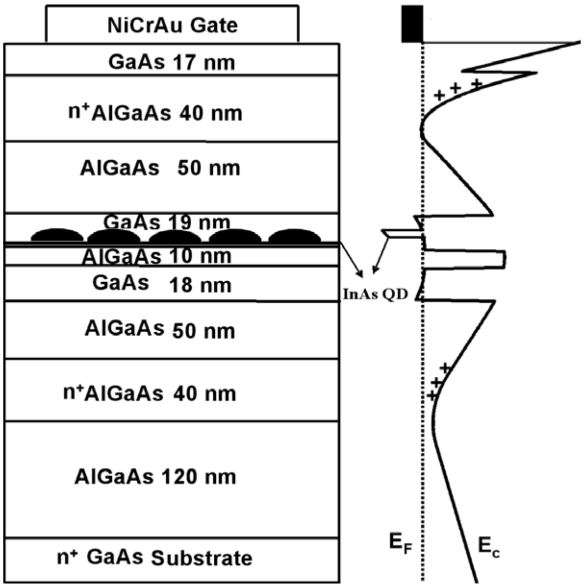

Figure 1. Schematic representation of the structure and conduction band diagram of the DQW structure embedded with InAs quantum dots.

modulation in the mobility of the 2DEG, which was found to increase or decrease depending upon the charged state of the QD [4–6]. However, in none of these studies was a hysteresis effect observed in the dark. Recently the electron transport hysteresis effect was observed in double quantum well (DQW) structures with no QDs as the gate voltage is swept up and down in the presence of a magnetic field [7]. This effect was attributed to the charge transfer between the two layers when the Fermi level in one layer jumps from one Landau level to another. However, this mechanism cannot be used reliably for memory device applications.

2. Experiment

In this present work we report the transport hysteresis effect in a (DQW) structure embedded with InAs QDs in the upper well. Figure 1 depicts the structure and conduction band diagram of the double quantum well sample under study. The sample was grown by molecular beam epitaxy and consists of two GaAs quantum wells separated by a 10 nm barrier. The lower well is 18 nm wide and the upper well has a width of 19 nm embedded with self-assembled InAs QDs at a distance of 4 nm from the tunnel barrier. The electrons were provided by the Si doping layer on each side of the quantum wells. The doping layers were separated from the quantum wells by an AlGaAs layer with a thickness of 500 Å. During the growth of the InAs QDs the temperature of the substrate was reduced from 660 to 555 °C. After the deposition of the InAs quantum dots, the temperature was raised and maintained at 660 °C for the remainder of the growth. The electron densities in the quantum wells are controlled by applying a bias through the front gate. Longitudinal and Hall resistance measurements were taken in the four terminal configurations as a function of the gate voltage using the standard lock-in detection technique at 1.5 K.

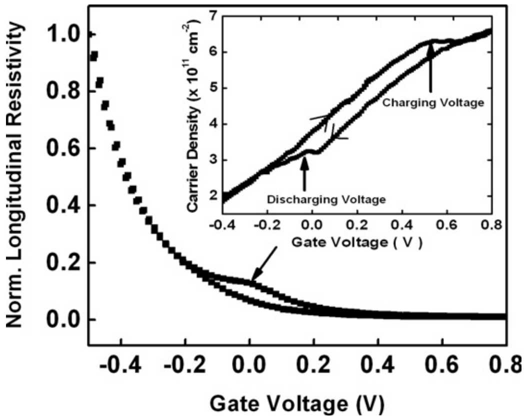

Figure 2. Zero field longitudinal resistivity as a function of gate voltage (V_g). The arrow corresponds to the point of inflection. Inset: variation of total carrier density as a function of V_g.

3. Results and discussion

Figure 2 shows the variation in the zero field longitudinal resistivity (ρ_{xx}) as the gate voltage (V_g) is cyclically scanned between −0.5 and 0.8 V. It is very much evident from the graph that the ρ_{xx} curve traces different paths for -0.2 V $< V_g <$ 0.4 V while scanning in the forward and reverse directions. The value of ρ_{xx} in this voltage range is found to be higher while reverse scanning the gate bias. The transport hysteresis loop is characterized by a point of inflection at around 0 V (indicated by the arrow) at which the ρ_{xx} trace makes a transition from being concave up to concave down. This observed feature is very different from the hysteresis behavior reported by other groups [4, 8].

Measurement of the Hall resistance at fixed magnetic fields of 0.1 and 0.3 T as a function of V_g was found to exhibit the same hysteresis effect as ρ_{xx}. In the range of -0.5 V $< V_g <$ -0.4 V, the value of ρ_{xy} was found to increase with increase in V_g as the electrons start to populate the upper well which was initially depleted of charge carriers (figure 3). No such features are observed in the ρ_{xx} trace. This is because the behavior of ρ_{xy} is determined by the transport properties of electrons at the edges. The probability of interaction between edge channel electrons within a quantum well is more pronounced when QDs are situated close to the 2DEG [9]. Therefore in the sample under study, when the upper 2DEG starts to populate the scattering between the edge channel electrons in both the layers contributes to ρ_{xy}. The net effect increases the overall Hall resistance and a broad peak is observed between −0.5 and −0.4 V in the Hall traces. However, no such increase in the ρ_{xx} trace is observed. In the case of ρ_{xx}, the interaction between the neighboring 2DEG depends upon the width of the barrier and the temperature [10]. For a barrier width of 10 nm and at 1.4 K the effect of interlayer electron interaction will not be clearly visible in the features of ρ_{xx} when compared to the features arising out of the interaction of the 2DEG with the QDs which are embedded in the quantum well itself. In the control sample with no QDs, we observed an increase in the ρ_{xx} value as the carrier starts to populate the upper quantum well. The absence of such features in our sample indicates that scattering due to QDs masks the effect of scattering due to interlayer electron interaction. Hence there is no signature of interlayer electron scattering in the ρ_{xx} traces.

The hysteresis phenomenon observed in the ρ_{xx} and ρ_{xy} trace can be explained by a simple intuitive physical picture on the basis of the difference in the number of electrons in the QDs while cyclically scanning the gate bias. The ramping of V_g from negative to positive values

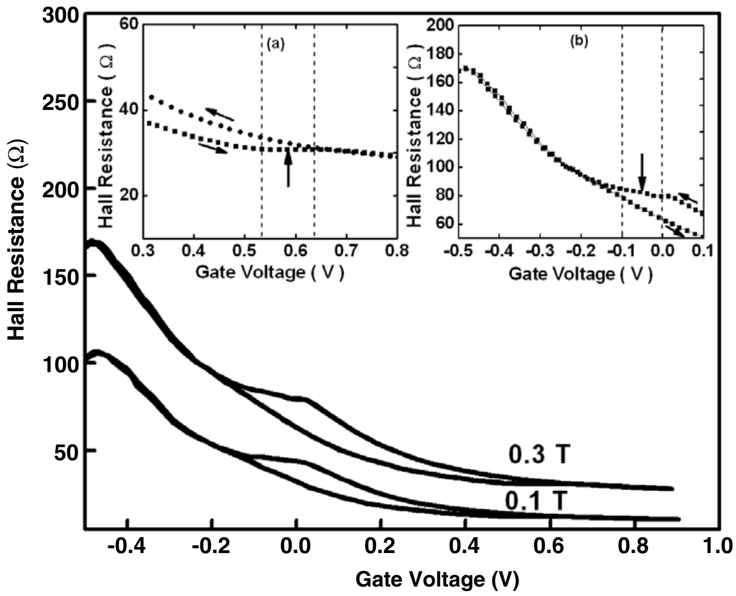

Figure 3. Hall resistance as a function of gate voltage at 0.1 and 0.3 T. Inset: magnified view of the Hall resistances at 0.3 T for (a) $0.3 < V_g < 0.8$ and (b) $-0.5 < V_g < 0.1$. The arrow between the two dotted lines indicates the change in the resistance slope between these voltage limits.

increases the carrier density of the upper well significantly when compared to the lower well due to the closer proximity of the former to the front gate. As the variation in carrier density in the upper well is greater when compared to the lower well, the difference in the chemical potential between the two wells generates an internal electric field which drives the electron from the lower well to the upper well across the tunnel barrier [11]. As electrons tunnel into the upper well, they populate the QDs which lie at a distance of 40 Å from the tunnel barrier. These charges get trapped in the intrinsic energy states of the QDs under suitable biasing conditions which correspond to the writing operation of the memory device. These stored charges are depleted when sweeping the gate bias to negative values. The presence of excess charge in the QDs during the reverse sweep increases the overall resistance due to the short range scattering induced by the potential of the dot causing pronounced deviation in the resistance traces. The difference in the charged state of the QDs gives rise to the hysteresis effect observed in ρ_{xx} and ρ_{xy} traces.

The bias at which the charging and discharging of electrons occurs within the QDs can be identified from the behavior of resistance and the carrier density traces, as V_g is cyclically scanned (figure 2). When the value of V_g is gradually increased during the forward sweep, the carrier density in the DQW system increases substantially and enhances the screening effect of the 2DEG. As a result, the scattering due to ionized donors which is the dominant scattering mechanism in the system is reduced and there will be a decrease in the ρ_{xx} and ρ_{xy} values [12]. The increasing electron density enhances the exchange and correlation energy of an electron system which promotes the transfer of an electron from a quantum well of low electron density (lower well) to one with higher density (upper well). This transfer of electrons takes place at the expense of capacitive energy. The electrons that are so transported across the barrier from the lower to the upper well are trapped in the intrinsic energy states of the QDs [13]. The flat region in the carrier density trace observed between $0.56\ \text{V} < V_g < 0.66\ \text{V}$ represents the tunneling regime between which the QDs are charged with electrons from the lower well and is shown in the inset of figure 2. Therefore during this tunneling process the voltage applied through the front gate is used for the tunneling process and for this particular range of V_g the density of the 2DEG remains almost constant even though V_g is increasing. At constant 2DEG density, the Fermi wavevector (k_F) and the Fermi wavelength (λ_F) also remain constant, resulting in the stabilization of the screening effect [14]. In this scenario the value of ρ_{xy} will be constant (indicated by an arrow) and is enclosed between the dotted lines (inset of figure 3(a)). Beyond the dotted lines, the slope of the resistance curves changes and they are no longer flat. During the discharging operation the carrier density decreases linearly with V_g and at a particular voltage value between 0 and −0.1 V electrons that are trapped in the QDs are released from it. This phenomenon slightly increases the overall 2DEG density (inset of figure 2). In this region the 2DEG screening ability is slightly enhanced and the rate of increase in the ρ_{xy} value decreases substantially in spite of the depleting bias which is observed between the range of V_g 0 and −0.1 V (inset of figure 3(b)). From this it is very evident that at 0.56 V the QDs begin to accumulate the charges and starts to discharge when V_g is ramped below 0 V.

One notable aspect of this feature is that even though the QDs are charged at 0.56 V, the depletion of trapped charges begins (flat region in the inset of figure 3(b)) only when the gate bias is ramped below 0 V. This result is very striking because it effectively indicates that the QDs charged during the forward sweep maintain their maximum charged state even in the absence of any external bias (0 V). This can have promising applications in non-volatile memory devices. Moreover, much less power is required for the operation of this device since the voltage range over which the above-mentioned effects are observed is between −0.5 and +0.8 V. This operating voltage value is less when compared to the values reported in the previous electrically driven QD based memory devices [15, 16]. It has to be mentioned that no hysteresis effect was observed in single quantum well structures embedded with quantum dots at the center. Hence, the hysteresis effect observed in our measurement process is a unique feature of the DQW system.

The enhancement in the charge retentivity stems from the compressibility (screening ability) of the 2DEG. In the DQW structure scanning the gate voltage from negative to positive value (forward sweep) and back again (reverse sweep) has completely contrasting effects on the QDs embedded in the upper well. For a large negative gate bias, the upper well is completely depleted and the carriers are confined in the lower well. As the gate bias is progressively made positive, the electrons start to occupy the upper well situated close to the gate. As the carrier density in the upper well is increased, the effect of voltage bias on the QDs decreases, due to the compressibility of the upper 2DEG which screens the electric field due to V_g. However, the dependence of the screening ability of the upper 2DEG on the carrier density is not straightforward. It undergoes a transition from a positive to negative value as the upper well carrier density is increased beyond a threshold value. In the study carried out by Millard *et al* it was reported that the 2DEGs have a negative compressibility at a higher carrier density and some of the field penetrates and influences the charge carriers in the QDs [16]. From the above-mentioned study it is very much evident that the electric field experienced by the QDs is very different when the gate bias is scanned in the forward and reverse directions.

During the forward sweep as V_g is made more positive, the compressibility of the 2DEG changes from a positive to negative value, and the electric field experienced by the QDs increases. This creates an ideal condition for the electrons to get trapped in the intrinsic energy states of the dots. During the reverse sweep, the situation is quite different. The compressibility of the upper 2DEG undergoes a transition from negative to positive values as the gate bias is decreased, which reduces the electric field experienced by the QDs. Hence, the QDs are effectively screened from the depleting gate bias and this allows them to hold charge even

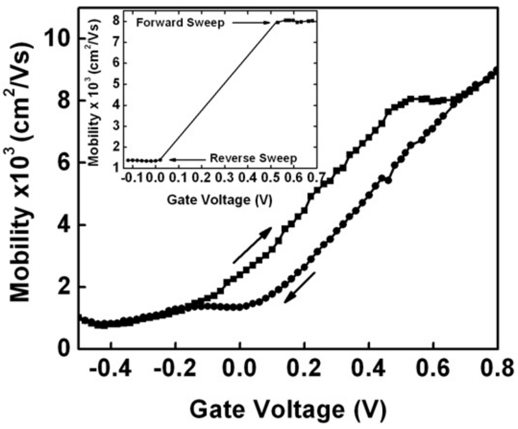

Figure 4. A plot of mobility versus gate voltage for forward and reverse sweeping of gate bias. Inset shows the bi-stability in the mobility of the 2DEG during the charging and discharging operation.

at 0 V. In order to deplete the charges, the gate voltage has to be ramped to more negative values. Therefore, once the QDs are charged by ramping V_g to 0.6 V, the charged state can be maintained even when the device is powered off. The presence of the upper 2DEG prevents the accidental discharge of stored charges by screening the charges trapped in the dots.

One notable aspect in the ρ_{xy} trace is the increase in the area of the hysteresis loop when the magnetic field is increased from 0.1 to 0.3 T. This is due to the fact that the applied magnetic field increases the confinement of the in-plane electron wavefunction within the quantum well. This localization of electron wavefunction increases the probability of carrier capture by the QDs. Therefore the number of electrons that are trapped in the potential of the QDs is greater at 0.3 T than at 0.1 T. The trapping of additional charges in the QDs increases the scattering potential in the 2DEG according to the equation

$$\langle U(q)\rangle^2 = N_{\rm qd}\left(\frac{2\pi \mathrm{e}^2}{\kappa q}\right)^2 \mathrm{F}(q,d)^2, \tag{1}$$

where $N_{\rm qd}$ is the density of electrons in the quantum dots, q is the scattering wavenumber, κ is the dielectric constant of GaAs, $\mathrm{F}(q,d)$ is the form factor which takes into account the finite extension of the 2DEG and the distance d between the plane of the quantum dot and the 2DEG [17]. According to the Stern–Howard model, the scattering rate in the 2DEG is a direct function of the scattering potential $U(q)$ and is given by the equation

$$\frac{1}{\tau_i} = \frac{1}{2\pi\hbar\varepsilon_{\rm F}}\int_0^{2k_{\rm F}} \mathrm{d}q \frac{q^2}{\sqrt{4k_{\rm F}^2 - q^2}} \frac{\langle |U(q)|\rangle^2}{\varepsilon(q)^2}, \tag{2}$$

where $\varepsilon_{\rm F}$ is the Fermi energy potential and $\varepsilon(q)$ is the dielectric function of the 2DEG [17]. From equation (2) it is clear that the enhancement in the scattering potential increases the rate of scattering between the edge channel electrons which increases the Hall resistance, resulting in wide hysteresis loop at 0.3 T when compared to 0.1 T (figure 3) [18, 19].

In figure 4 the mobility of the 2DEG is plotted as a function of V_g and is found to exhibit a similar hysteresis loop to those of ρ_{xx} and ρ_{xy}. The mobility is calculated by using the formula $\mu = (\rho_{xx} n\mathrm{e})^{-1}$ where 'n' is the total carrier density of the 2DEG determined from the Hall slope ($R_{\rm H} = 1/n\mathrm{e}$) and ρ_{xx} is the zero field resistivity. In the region 0.56 V $< V_g <$ 0.66 V during the forward sweep and -0.1 V $< V_g < 0$ V during the reverse sweep, the mobility was found to have a constant value. The range of V_g in which the mobility has a stable value exactly corresponds with the charging and discharging voltage regime. This is due to the fact that during the charging and discharging operation the value of ρ_{xx} is constant (figure 2) and any change in the value of 'n' is compensated for by the trapping and releasing of electrons from the QDs as mentioned earlier. Hence the mobility of the 2DEG remains constant and in the inset of figure 4 the mobilities corresponding to the two flat regions are plotted and connected by a straight line. The mobility of the 2DEG differs by a factor of 6 between the charged and discharged state and hence it can be used as a sensitive detector to detect the writing and reading operation.

4. Conclusions

In conclusion, we have investigated the transport hysteresis in a DQW structure embedded with QDs in the upper well. The longitudinal and Hall resistances exhibited a hysteresis effect as the gate voltage was cyclically scanned between −0.5 and 0.8 V. The transport hysteresis effect is attributed to the charging effect of the InAs QDs. The presence of the 2DEG in the upper well acts as a screening medium which prevents the rapid depletion of the electrons from the QDs during the reverse sweep. The trapped charges in the QDs are found to exist even at zero bias which could have promising applications in memory devices. A more detailed study is required to precisely determine the charge retention time in the QDs and explore the possibility of room temperature operation. This will be left as a subject for future experimental studies.

Acknowledgment

This work was supported by the Korea Science and Engineering Foundation (KOSEF) grant funded by the Korea government (MOST) (No. R0A-2007-000-10032-0).

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