Experimental studies of T–shaped quantum dot transistors: phase-coherent electron transport

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Abstract

We have measured the low-temperature transport properties of a T-shaped quantum dot. Replicated oscillations superimposed on one-dimensional conductance steps are observed. These structures are consistent with electron phase-coherent length resonance effects in the ballistic regime. Using a simple model, we suggest that both one-dimensional and two-dimensional electron-electron scattering gives rise to electron phase-breaking in our system.

Key words: A. heterojunctions, semiconductor. D. electron transport.
The ballistic transport of electrons confined in one-dimensional (1D) systems has been extensively studied both experimentally and theoretically. Conductance quantisation observed in split-gate devices [1,2] provides clear evidence for ballistic transport. The interference features observed in a split-gate device [3] and in double-slit experiments [4] have clearly demonstrated the existence of phase coherent-electron transport in the ballistic regime. For a ballistic channel patterned with barriers, there are predictions of electron phase-coherent length resonance effects [5,6] in such a structure. Therefore oscillations superimposed on ballistic conductance steps may be observed in this regime as has been recently reported when there is only one 1D subband occupied [7].

We have now extended our previous work and in this Communication, we present experimental studies of a T–shaped quantum dot transistor. We observe replicated conductance oscillations superimposed on 1D conductance steps which are interpreted as electron phase-coherent length resonance effects in the ballistic channel. The magnetic field and temperature dependence of these structures will be described. Four samples showed similar characteristics, and measurements taken from one of these are presented in this paper.

The Schottky gate pattern shown in the inset to Fig. 1 was defined by electron beam lithography on the surface of a GaAs/Al\textsubscript{0.3}Ga\textsubscript{0.7}As heterostructure, 100 nm above a two-dimensional electron gas (2DEG). The carrier concentration of the 2DEG is $4.7 \times 10^{15}$ m$^{-2}$ with a mobility of 150 m$^2$/Vs. Experiments were performed in a $^3$He cryostat at 300 mK and the two-terminal differential conductance $G = dI/dV$ was measured using an ac excitation voltage of 10 $\mu$V.
Patterning of the underlying 2DEG most closely mirrors the shape of the lithographically defined metallisation at the gate voltage when depletion just occurs under the 100 nm width fingers. This is at a higher voltage than that needed to deplete carriers from beneath the wider metallisation due to fringing effects. Therefore the maximum potential modulation along the channel is obtained when one side of the device is maintained at a constant voltage and the other is swept to reduce the device conductance [7,8]. In our case, experiments were performed with one side of the device at a fixed voltage and the other gate is swept. Figure 1 shows $G(V_{g1})$ for a fixed $V_{g2}$ in two different cooldowns. In both cases we observe similar structures, in particular two conductance dips superimposed on two 1D conductance steps, suggesting that impurity scattering is not significant in our system, and the oscillating features primarily arise from the potential landscape in the channel defined by the lithographic pattern. We interpret these conductance oscillations as electron phase-coherent length resonance effects between two barriers.

Figure 2 shows $G(V_{g1})$ for $V_{g2} = -1.4$ V at various magnetic fields $B$. The oscillations superimposed on the conductance steps gradually disappear as $B$ is increased. The application of a perpendicular magnetic field breaks time reversal symmetry, suppressing coherent backscattering of electrons in the ballistic channel. This is analogous to suppression of weak localisation effects in diffusive transport by a perpendicular magnetic field.

Figure 3 shows $G(V_{g1})$ for $V_{g2} = -1.4$ V at different temperatures $T$. As $T$ is increased, the conductance oscillations become weaker and we recover ballistic conductance steps. This effect is due to a reduction in phase coherence time at higher temperatures, leading to an enhancement of phase-breaking rate.
we use a simple model to determine the electron phase-breaking mechanism in our system. Provided that the amplitude between a peak and a trough in conductance oscillations $Amp$ is given by

$$Amp \propto \exp(-\tau/\tau_\phi), \quad (1)$$

where $\tau$ and $\tau_\phi$ are the traversal time for electron to pass through the ballistic channel and electron phase coherence time, respectively. From this we know that

$$\ln(Amp) \propto -\tau/\tau_\phi + A, \quad (2)$$

where $A$ is a constant. Here we assume that the traversal time $\tau$ is temperature independent which holds when the thermal broadening is much smaller than the Fermi energy in our case. From the amplitude of the conductance oscillations at various temperatures, we have

$$\ln(Amp(T)) \propto -1/\tau_\phi(T) + A/\tau. \quad (3)$$

Figure 4 shows the normalised logarithm of the conductance oscillations amplitude on the second step (marked by circles) and on the first step (marked by squares) as a function of temperature. From the fit we obtain $1/\tau_\phi(T) = 0.2147 T + 0.0717 T^2 \ln(T)$. There are two physical mechanisms which can give rise to the linear term in $T$: 2D electron-electron scattering [9–11], enhanced by disorder in the diffusive limit [12,13], and electron-electron scattering in the clean metallic regime where only a small number of 1D subbands are occupied [14]. In our system, at elevated temperatures we observe well quantised conductance steps, demonstrating that our device is in the ballistic rather than
the diffusive limit. Moreover, the product $k_F l$ in the bulk is $\approx 3000$ where $k_F$ is the Fermi wave-vector and $l$ is the elastic scattering length, respectively, indicating that the device is in the clean metallic regime. Combining these two facts, we conclude that the linear term in $T$ corresponds to electron-electron scattering in 1D in the clean metallic limit [14] whereas the $T^2 \ln(T)$ term corresponds to the well-known electron-electron scattering in 2D [15,16]. The results suggest that both 1D and 2D electron-electron scattering are important in our system: 2D scattering occurs in the wide regions of the channel where there are many subbands occupied, whereas 1D electron scattering takes place around two barriers, the narrow regions of the channel where only one or two subbands are occupied.

In conclusion, we have measured the low-temperature transport properties of a T–shaped quantum dot transistor. We have observed replicated oscillations superimposed on ballistic conductance plateaux which are interpreted as electron phase-coherent length resonance effects in the ballistic channel. Using a simple model, we suggest that electron-electron scattering both in one and two dimensions introduces electron phase-breaking in our system. As we have well characterised T–shaped quantum dot devices, in future this work can be extended by investigating a finite-period T-shaped dot array [17] where formation of energy gaps arising from Bragg reflections in an artificial lattice is expected to be observed in zero magnetic field.

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Figure Captions

Figure 1. Lower curve: differential conductance measurements as a function of gate voltage $G(V_{g1})$ for $V_{g2} = -1.4$ V in the first cooldown. Higher curve (offset by 50 $\mu$S for clarity): $G(V_{g1})$ for $V_{g2} = -1.72$ V in the second cooldown. The inset shows the device geometry.

Figure 2. $G(V_{g1})$ at various magnetic fields $B$ for $V_{g2} = -1.4$ V. From bottom to top: $B = 0$ to 1 T in 0.1 T steps. Traces are successively offset by 30 $\mu$S for clarity.

Figure 3. $G(V_{g1})$ at different temperatures for $V_{g2} = -1.4$ V. From bottom to top: $T = 0.3$ K to 1.5 K in 0.1 K steps and $T = 1.85$ K to 3.25 K in 0.1 K steps. Curves are offset successively by 15$\mu$S for clarity.

Figure 4. Normalised logarithm of the amplitude $Amp$ of the conductance oscillations on the first conductance step (marked by squares) and on the second step (marked by circles) at various temperatures $T$. The solid line shows a fit $\ln(Amp(T)) = -1.09 - 0.2147 T - 0.0717 T^2 \ln(T)$. 
