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Probing e-e interactions in a periodic array of GaAs quantum wires

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Abstract

We present the results of non-linear tunnelling spectroscopy between an array of independent quantum wires and an adjacent two-dimensional electron gas (2DEG) in a double-quantum-well structure. The two layers are separately contacted using a surface-gate scheme, and the wires are all very regular, with dimensions chosen carefully so that there is minimal modulation of the 2DEG by the gates defining the wires. We have mapped the dispersion spectrum of the 1D wires down to the depletion of the last 1D subband by measuring the conductance G as a function of the in-plane magnetic field B, the interlayer bias $V_{\rm dc}$ and the wire gate voltage. There is a strong suppression of tunnelling at zero bias, with temperature and dc-bias dependences consistent with power laws, as expected for a Tomonaga-Luttinger Liquid caused by electron-electron interactions in the wires. In addition, the current peaks fit the free-electron model quite well, but with just one 1D subband there is extra structure that may indicate interactions.

Key words: tunnelling, e-e interactions, Luttinger liquid, quantum wires, double quantum wells (DQWs)
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Electron-electron interactions in a one-dimensional (1D) metal are predicted to cause the formation of a Tomonaga-Luttinger Liquid (TLL) in which there are both elementary spin and charge excitations. Other properties of the TLL have been studied in a variety of systems (see e.g. [1]), but only a few have attempted to detect the spin-charge separation directly, e.g. by photoemission [2] and tunnelling [3,4] spectroscopy.

Following measurements of the spectral function of 1D wires by Kardynal *et al.*,[5] Altland *et al.*[6] proposed their use in detecting the spin-charge separation. The tunnelling current I between the 1D wires and an adjacent low-disorder 2D layer depends on the overlap between the spectral functions of the two systems, which is varied by using an in-plane magnetic field B perpendicular to the wires to offset the two in k-space; a bias $V_{\rm dc}$ between the layers is used to investigate the energy dependence. In a non-interacting system, peaks in the conductance G follow the 1D and 2D subbands. In contrast, for a TLL, there should be two features, for spin and charge, instead of one for a non-interacting 1D subband.[6,7]

We have previously used ion-beam lithography to make separate contact to two such layers of electrons, for investigating arrays of 1D wires[8] and antidots[9], but here we adopt a simpler technique that uses just

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surface gates and allows measurements even when the last 1D subband is nearly depleted. With this technique, we probe the single-particle spectrum of the 1D system down to single subband. We also find a zero-bias anomaly (ZBA) in which the tunnelling current between a single 1D subband and the 2D electron gas (2DEG) is strongly suppressed at low temperatures.

The 1D system was formed as a array of long wires on a double-quantum-well (DQW) structure. The wafer comprised two identical 18 nm GaAs quantum wells separated by a 14 nm $Al_{0.33}Ga_{0.67}As$ tunnel barrier. 40 nm Si-dopant layers ($\sim 10^{18}$ cm^{-3}) above and below the two quantum wells provide electron concentrations of $2.8\,(1.64)\times10^{11}$ cm^{-2} with mobilities of about $8\,(5)\times 10^5$ cm^2 V^{-1} s^{-1} in the top (bottom) well, as measured at 1.8 K. The device was processed into a 100 μm-wide Hall bar. Electron-beam lithography was used to define an array of $17.5 \times 0.1\mu$m wire gates (WG) with a 270 nm period, all the way across the mesa (see Fig. 1(c)).

The two-terminal conductance $G = \mathrm{d}I/\mathrm{d}V_{\rm dc}$ was measured at temperatures T down to <100 mK using an ac excitation voltage of 5 μV at 77 Hz added to a dc voltage. Independent Ohmic contacts to the individual layers were achieved by a surface-gate depletion scheme[10]. Here, a split gate SG, positioned at one end of the wires (see inset, Fig. 1), was biased to $V_{\rm sg} = -2.25$ V, and a 'mid-line' gate (MG) was set to $V_{\rm mg} = +0.60$ V. This defined a conducting 1D channel only in the top 2DEG. An additional depletion gate labelled BG was biased as $V_{\rm bg} = -0.56$ V in order to isolate the top 2DEG from the drain Ohmic contact. Current was carried by electrons tunnelling between the layers in the region of length L between SG and BG. A negative bias $V_{\rm wg}$ on the gate wires (of length l) nearly covering the whole tunnelling area depleted the upper 2DEG into an array of 1D wires. However, a small ungated region h of width $L - l = 0.9\mu$m provides a current path to the entrances to the 1D wires. The widths of h and of the wire gates were chosen carefully such that even with just a single 1D subband in the top 2DEG the wires remained conducting with minimal modulation of the lower 2DEG. The long narrow 2D h region inevitably contributes a 2D parallel tunnelling path that appears in the measurements. However, this is small and independent of the tunnel current from the wires.

The magnetic field B shifts the origin of the 2D Fermi circle in k-space relative to that of the 1D system by $k_{\rm x} = eBd/\hbar$, where d is the centre-to-centre tunnelling distance between the two quantum wells and the x-axis is along the wires. Tunnelling occurs at overlapping parts of the two spectral functions and conserves the electron energy and momentum. By applying a positive bias $V_{\rm dc}$ to the 2DEG, electrons tunnel into excited states of the 2DEG, from matching states below the Fermi energy in the 1D wires. At $V_{\rm dc} = 0$, there is a series of peaks as a function of B voltage. As shown in Fig. 1(a), there is a pair of peaks $B_i^{\pm}$ for the i-th 1D subband. Six peaks are observed at $V_{\rm wg} = -0.487$ V (upper trace, Fig. 1(a)), corresponding to three occupied 1D subbands. With decreasing $V_{\rm wg}$, the 1D subband spacing increases and the 1D density decreases. Hence the number of subbands can be reduced to just one. At $V_{\rm wg} \sim -0.65$ V the wires become insulating but $V_{\rm wg}$ is too small to pinch off the bottom 2DEG. Some parasitic current can flow via tunnelling in the parallel region h. Normalising the conductance (Fig. 1(b)) reveals the depletion of each subband and the 2D-2D parasitic tunnelling peaks. The bottom 2DEG becomes depleted at $V_{\rm wg} = -0.82$ V.

Fig. 2 shows G as a function of the DC interlayer bias ($V_{\rm dc}$) and B as a greyscale plot at $V_{\rm wg} = -0.62$ V, well into the region where there is just one 1D subband. In the absence of interactions, there should be peaks in G that follow the 1D and 2D parabolic dispersion rela-

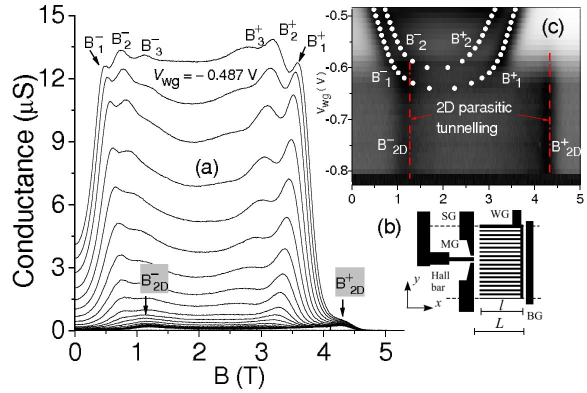

Fig. 1. (a) Tunnelling conductance G showing resonant peaks in the transverse magnetic field measured at 1.8 K. $V_{\rm wg}$ was incremented from -0.487 V (top curve) to -0.90 V in steps of 12 mV. (b) Device layout; gates are shown in black. (c) Greyscale of the data in (a), normalising each trace to the same maximum height. Dark regions are peaks in G, with the white dots on top indicating the first and second 1D subbands, respectively. The 2D parasitic tunnelling from region h does not change with $V_{\rm wg}$ – its peaks stay at 1.27 T and 4.31 T, represented as dash lines.

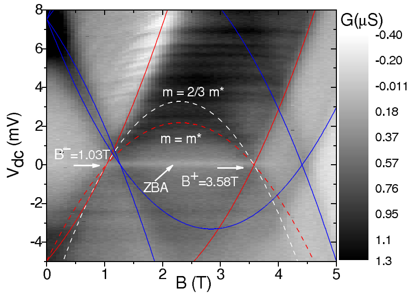

Fig. 2. Tunnelling conductance G vs $V_{\rm dc}$ and B.

tions, shown as lines. The parasitic 2D-2D tunnelling in the ungated h region is also shown, as thick blue lines that intersect B=0 at +7.5 meV, where for 1D-2D tunnelling is occurred at −5 meV, as red. The crossing points along $V_{\rm dc} = 0$ are obtained at $\mathrm{B}^- = 1.03$ T and $\mathrm{B}^+ = 3.58$ T, giving the electron density in the wires $n_{\rm 1D} \simeq 40\mu\mathrm{m}^{-1}$. These two sets of dispersions can be distinguished clearly and their singularities follow the lines well. This is in good agreement with our calculated single-particle results, such as the negative conductance at the top left where we use the electron effective mass in GaAs ($\mathrm{m}^* = 0.067\mathrm{m_e}$) and $d = 32$ nm in our system. However, a lower effective mass such as 2/3 m^* may fit the broad peak better; this could be caused by interactions in the wires.

Moreover, a feature that cannot be explained in the noninteracting model is the 'zero-bias anomaly' (ZBA), the strong suppression of conductance along $V_{\rm dc} = 0$, visible as a bright line in Fig. 2. This is likely to be related to the energy cost for an electron to tunnel into or out of a 1D wire, as it disturbs the line of electrons on either side of it. It has previously been observed in 1D-1D tunnelling[3] and G is expected to have power-law dependences on $V_{\rm dc}$ and temperature T.

Fig. 3 shows the ZBA as a function of $V_{\rm dc}$ at various temperatures (inset (a)) close to $B = B_1^-$, and midway between B_1^- and B_1^+ (where the parasitic conductance is almost negligible) (inset (b)). The main graph shows the value of the ZBA minimum as a function of T as in inset (a) and of $V_{\rm dc}$ (as in inset (b)), both on log-log axes. The power-law exponent α found from the slopes of $G(T)$ and $G(V_{\rm dc})$ are similar, $\alpha = 0.4 \pm 0.1$, and comparable to that found for cleaved-edge overgrown quantum wires [3].

In summary, we have measured momentum-resolved tunnelling from a 1D electron system fabricated as an

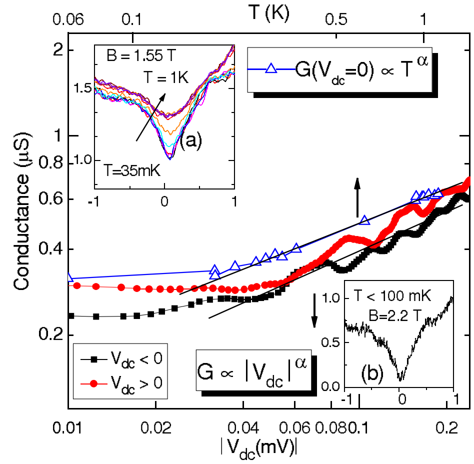

Fig. 3. Minima of the ZBA *vs* T for $B = 1.55$ T (0.3μS was subtracted to allow for the parasitic current) and $G(V_{\rm dc})$ for $B = 2.2$ T. Inset (a): ZBA at various T up to 1.2 K at $B = 1.55$ T. Inset (b): $G(V_{\rm dc})$ on a linear scale.

array of GaAs quantum wires, into a high-mobility 2D electron gas. The number of occupied subbands can be reduced from three to one using a gate voltage. For the last 1D subband we have mapped the single-particle excitation spectrum of the tunnelling conductance. A strong suppression of the tunnelling current at zero bias (the zero-bias anomaly, ZBA) shows that interactions are very important in these 1D wires. The extracted TLL power-laws are consistent with wires made by cleaved-edge overgrowth.

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