Observation of dynamical ordering in a confined Wigner crystal

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Abstract

We demonstate the fabrication and control of surface state electrons on superfluid helium in microchannel devices. The response of these devices shows strong non-linearities, associated with dynamical ordering of the electrons in a confined geometry.

Key words: Single Electron Tunneling; Electrons on helium; Qubits

Surface state electrons (SSE) on liquid helium have been suggested as potential qubits [1][2] with electrons trapped above a helium film on a micro-structured substrate [3]. Experiments are now in progress in several laboratories. Creating and successfully operating devices to control small numbers of electrons is technically challenging. An electron control device has been created and used [4] that confines surface electrons in helium filled micron sized channels (microchannels) with about 18 electrons confined across the channel width and as few as 600 electrons above the controlling gate electrode.

The movement of these confined electrons along the channel, in response to an in-plane electric field E, is highly non-linear. A model was developed in which current filaments form across the channel width, with (fast) electron-fluid edge currents, and a (velocity limited) central current of spatially ordered electrons [5] at low temperatures. The mechanism for this is a divergent drag force due to the Bragg Cerenkov (BC) scattering of a 2D electron crystal, as the electron drift velocity v approaches v_1, the ripplon phase velocity at the reciprocal lattice vector [6][7]. An ohmic region is observed only for $v < v_1$. For mean velocities $\overline{v} > v_1$, a non equilibrium phase transition [5] occurs as the filamentary edge currents grow at the expense of the central region, which is dynamically pinned to a velocity v_1. In this region the electric field remains constant at $E_{\max}$ as $\overline{v}$ increases. Figure 1 shows the measured electric field E and the differential dE/dv $(= 1/\mu)$ versus the electron velocity $\overline{v}$ (the $V - I$ characteristic for the device). The linear region below v_1 and $E_{\max}$ can be seen.

We now present data that shows the dependence of $E_{\max}$ on SSE surface density and the BC scattering effect on the $E(v)$ characteristic with temperature.

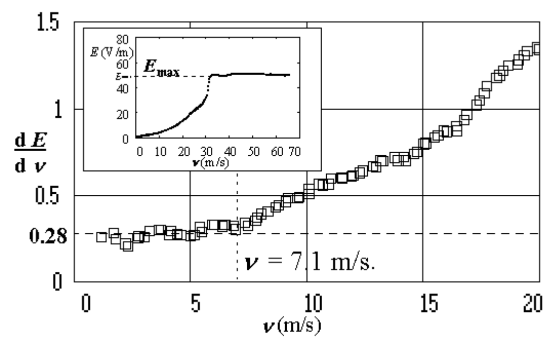

Fig. 1. The in-plane electric field E and δ E/δv vs the mean electron velocity v at 0.52 K and a density of 9.7×10^{12} m^{-2}, which gives a $v_1 = 7.1$ m/s.

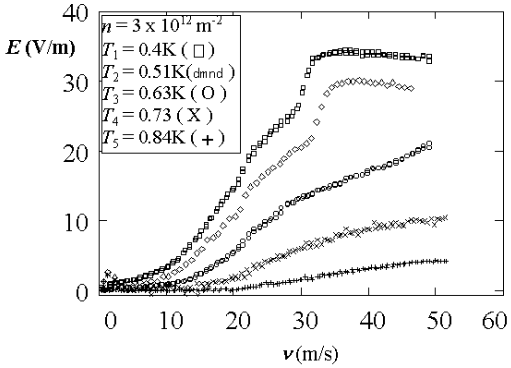

Fig. 2. :*E(v)* at temperatures of 0.4K(□), 0.51K(◇), 0.63K(o), 0.73K(x) and 0.84K(+).

Figure 2 shows the temperature dependence of $E(v)$ for an electron density $n = 3.0 \times 10^{12}\ \mathrm{m}^{-2}$ at temperatures between 0.4 and 0.8 K. At high temperatures, the response is almost linear. As the temperature falls, the electric field increases rapidly for a given velocity until the plateau region of constant E becomes well developed below 0.5 K. The electron solid melting temperature $T_\mathrm{m} = 0.39$ K. Non-linear effects are pronounced below T_m but are also observed at higher temperatures. Molecular dynamic simulations have shown evidence for electrons forming spatial ordered structures above T_m [8] and Monte Carlo simulations shows electron ordering in confined geometries [9][10][11] above the bulk melting temperature.

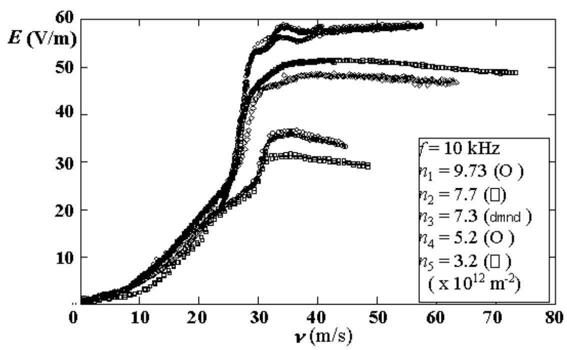

Fig. 3. $E(v)$ at densities of 3.2(□),5.2(o),7.3(◇),7.7(□) and 9.73(o)$\times 10^{12}$ m^{-2}at 0.45K.

The density dependence of $E(v)$ and E_max is shown in Figure 3 at 0.45 K and densities between 3.1 and $9.7 \times 10^{12}\ \mathrm{m}^{-2}$. In each case the plateau region is clearly observed and the value of E_max increases with density. The increase of E_max with density is due to the increased vertical pressing field which increases the electron-ripplon interaction. Some structure in $E(v)$ can be seen in the plateau at the highest density. Further experiments in this region suggested the formation of lines of electrons in the microchannels just above T_m [5].

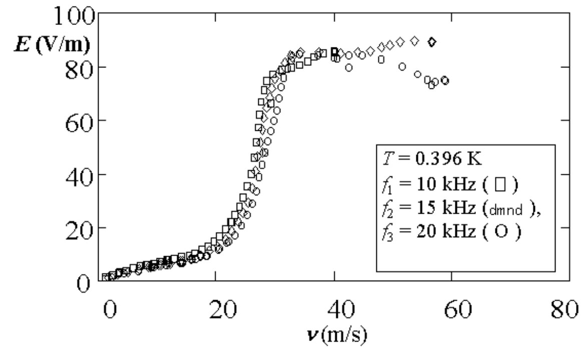

Fig. 4. $E(v)$ at drive frequencies of 10 kHz (□),15 kHz (◇) and 20 kHz (O) for $n = 9.7 \times 10^{12}$ m^{-2} ($T_\mathrm{m} = 0.527$ K).

Figure 4 shows the $E(v)$ characteristics for three different ac measurement frequencies close to the nominal melting temperature at 0.527 K for a density $n = 6.0 \times 10^{12}\ \mathrm{m}^{-2}$. This data confirms that the electron velocity is the key parameter, and not the drive voltage, as the capacitively coupled current is proportional to the frequency.

In conclusion, we have demonstated the fabrication and control of electrons on helium in microchannel devices. The response of these devices shows strong nonlinearities, associated with dynamical ordering of the electrons in a confined geometry.

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