Sliding Dynamics of the Wigner Crystal on Liquid He

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The Wigner crystal on liquid He accompanies with periodic corrugation of the He surface; dimples. The dynamics of the crystal is coupled with the motion and the deformation of the dimples. Nonlinear phenomena found in AC Corbino conductivity are attributed to the collective sliding of the electrons out of the dimples. In order to inspect the dynamical transition to the sliding state, we have developed a novel experimental method using a so-called "t² pulse", whose leading and trailing edges change in proportion to the square of time; \( V \propto t^2 \). Since the force exerting upon the crystal is proportional to the time derivative of the input voltage, \( dV/dt \), the \( t^2 \)-pulsed method is expected to realize a continuous sweep of the driving force, resulting in the real-time observation of the sliding transition. The observed response shows clearly the sliding, revealing that the external force to the crystal determines the sliding transition.

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1. INTRODUCTION

Surface state electrons on liquid He form the Wigner crystal at low temperatures, accompanying with periodic surface deformation, referred to as dimples. The Wigner crystal with the dimples has been discussed in terms of the coupled plasmon-riplpon (CPR) model\(^1\) and its first observation has been carried out by the measurement of the CPR resonance\(^2\). The dynamics of the Wigner crystal is governed by the motion and the deformation of the dimples, because each of the electrons composing the Wigner crystal is located in a potential caused by each of the dimples.
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Recent studies of AC Corbino conductivity $\sigma_{xx}$ of the Wigner crystal reveals an abrupt jump of $\sigma_{xx}$ at a certain driving voltage and at a moderate magnetic field. This conductivity jump is attributed to the collective sliding of the electrons out of the potential. In the $\sigma_{xx}$ measurement, a sinusoidal voltage is applied to the inner Corbino electrode coupled to the surface electrons capacitively, and the resulting current is measured via the outer electrode with a lock-in amplifier. The signal averaging makes the detailed investigation of the sliding dynamics difficult.

A transport study using a voltage pulse, on the other hand, makes real-time observation of the sliding achievable. The measurement with a trapezoidal pulse elucidates that the dynamics of the Wigner crystal is subjected by the ramp rate of the input voltage, $v = dV/dt$. This is understood in terms of the sliding model. In the present conditions, $\sigma_{xx}$ is so large that the current inside of the Wigner crystal is dominated by the impedance of the capacitance between the surface electrons and the Corbino electrode; hence, the current density $j$ at the electrode gap is proportional to $dV/dt$. Since the external driving force to each of electrons is given by $e\sigma_{xx}^{-1}j$, the driving force is proportional to $dV/dt$. Although this model does not take into account the current inhomogeneity inside the surface electron, it gives a basis for understanding the nonlinear dynamics of the Wigner crystal.

In the trapezoidal pulse study, $dV/dt$ change discontinuously at the edges of the pulse. This means that the Wigner crystal receives an impulsive force at the pulse edges. It is therefore inappropriate to employ the trapezoidal pulse to inspect sliding mechanism in detail. The continuous sweep of the driving force is obviously needed to investigate the dynamics of the transition from the dimpled state to the sliding one and vice versa.

In the present work, we have developed a novel experimental method using a so-called "$t^2$ pulse", in which the leading and trailing edges of the applied voltage pulse are proportional to the square of time, $V \propto t^2$. Employing the $t^2$ pulse, the ramp rate changes as $dV/dt \propto t$, resulting in the continuous sweep of the driving force. Consequently, it is expected that the sliding transition is induced in sweeping the driving force, leading to real-time observation of the sliding dynamics. In this paper, we report the observation of the sliding transition brought about by the $t^2$ pulse. We have revealed that the sliding transition is governed by only the ramp rate.

2. EXPERIMENTAL

As well as the previous works, we have employed the capacitive coupling method with a Corbino electrode. A voltage pulse is applied to the inner electrode, and the response current in the radial direction is measured.
Fig. 1. (a) The first half of the input $t^2$ pulse $V_{in}$, and response $V_{out}$ for $B = 0$ G and 690 G, where the response is normalized to the height of $V_{in}$. The inset shows the whole waveform of the $t^2$ pulse. (b) The time derivative of the response. At 690 G, the sliding transition appears clearly at $t_c$, where the threshold ramp rate $v_c$ is defined as $(dV/dt)_{t=t_c}$.

as an induced voltage at the outer electrode against the ground. The typical waveform of the applied $t^2$ pulse is shown in the inset of Fig. 1(a). The input voltage is ramped up to a height $V_0$ with a rise time $t_0$, where the voltage $V$ increases in proportion to the square of time; $V \propto t^2$. After the $t^2$ ramp up, the voltage was kept at $V_0$ for 100 $\mu$s, and then ramped down to zero with $V \propto t^2$ in a duration $t_0$. This pulse is applied at every 200 $\mu$s. The response is acquired by a digital storage oscilloscope and is averaged 10000 times.

The electrons are generated at 1.4 K by thermionic emission of a tungsten filament. The present electron density is $1.52 \times 10^8$ cm$^{-2}$. The measurement is carried out at 60 mK, much lower temperature than the melting point of the present Wigner crystal, 250 mK. A static magnetic field $B$ up to 700 G was applied perpendicular to the surface of the liquid He.

In order to compare the $t^2$-pulse results, we have made the $\sigma_{xx}$ mea-
Fig. 2. The critical ramp rate $v_c$ as a function of the rise time $t_0$, where the pulse height $V_0$ is fixed at 700 mV as shown in the inset. The broken line denotes $v_c$ derived from a trapezoidal pulse measurement.

surement using a 100 kHz sinusoidal wave and have measured the responses for the trapezoidal voltage pulses.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1(a) shows the first half of the input $t^2$ pulse $V_{in}$ ($V_0 = 700$ mV and $t_0 = 20$ µs) and the response $V_{out}$ for $B = 0$ G and 690 G. At 0 G, the response follows the input pulse with a very short delay below 1 µs. At 690 G, on the other hand, the response shows remarkably long delay at $t > t_c \sim 5.7$ µs. This delay becomes more prominent by taking the time derivative of the response, $dV/dt$, as shown in Fig. 1(b). At 0 G, $dV/dt$ increases linearly, indicating that the response trails the input waveform. At 690 G, in contrast, the response shows an anomaly, that is, $dV/dt$ deviates from the linear tendency with a large delay at $t > t_c$.

Our previous studies on the nonlinear transport of the Wigner crystal employing both continuous waves (CW) and trapezoidal pulses illustrate that the sliding transition is brought about when the ramp rate of the applied voltage exceeds a certain critical rate. In the trapezoidal-pulsed study, moreover, the sliding is observed as a sudden increase of the response delay. Therefore, the present behavior of the $t^2$-response waveform at $t > t_c$ means the sliding transition of the Wigner crystal induced by the $t^2$ pulse. Based upon the data shown in Fig. 1, we determine the critical ramp rate $v_c \equiv (dV/dt)_{t=t_c} = 1.8 \times 10^4$ V s$^{-1}$.
Fig. 3. $v_c$ as a function of the applied magnetic field $B$. Closed circles denote $v_c$ obtained from the CW measurement. Others are obtained from $t^2$ responses, where $t_0$ and $V_0$ are shown in the inset.

We have made the above measurements for various $t_0$'s. In Fig. 2, $v_c$ is shown as a function of $t_0$ for a fixed $V_0 = 700$ mV. The critical ramp rate obtained from the trapezoidal pulse measurement is also shown as a broken line. In the $t^2$-pulsed method, $v_c$ is irrespective of $t_0$, although it ranges from 2.0 to $2.5 \times 10^4$ V s$^{-1}$. This indicates that the sliding transition is not subjected by the rise time, but by the ramp rate of the input pulse. Moreover, $v_c$ is fairly close to the one obtained in the trapezoidal pulse measurement, $1.9 \times 10^4$ V s$^{-1}$. This agreement convinces that the sliding state caused by the $t^2$ pulse is the same state as the one induced by the trapezoidal pulse.

We have found that $v_c$ obtained from the $t^2$ pulse is always slightly larger than that in the trapezoidal method. This may be substantial, because the sliding transition can be dominated not only by the voltage ramp rate but also by the history in the applied voltage. In short, the impulsive force produced at the edges of the trapezoidal pulse may activate the sliding. This proposition must be clarified by the detailed analysis of the response waveform below and above $v_c$, and it will be discussed elsewhere.

Figure 3 shows the magnetic field dependence of $v_c$ for various pulse conditions, together with the $v_c$ data obtained from the $\sigma_{xx}$ jumps in the 100 kHz continuous wave measurement. All the $v_c$ data collapse onto a single line in the log-log plot, showing the powerlaw behavior: $v_c \propto B^{-0.73}$. 
This behavior is consistent with the result in our previous work, where the powerlaw is explained by the transition from the CPR state to a non-CPR state. As regards the $t^2$-pulsed studies, $v_c$ is in good agreement with the one obtained from the $\sigma_{xx}$ jump. Again this fact shows that the present transition brought about by the $t^2$ pulse is the same phenomenon caused by the continuous wave. In the $t^2$-pulsed studies, $v_c$ is not obtained below 300 G, because the delay of the response has not been observed. The reason has not yet been clarified. We suppose that the disappearance is not intrinsic property of the pulsed method, because the sliding transition has been verified in the trapezoidal pulse response down to 200 G. Employing the $t^2$ pulses with different $V_0$ and/or $t_0$ may make the observation of the sliding transition at the lower magnetic field possible.

4. CONCLUSION

In order to inspect the sliding dynamics of the Wigner crystal in real-time, the pulsed method employing a $t^2$ pulse has been developed, where the exerting force upon the Wigner crystal is swept continuously. The sliding transition of the crystal is induced by the $t^2$ pulse as well as by a trapezoidal one. The sliding is determined by the ramp rate of the input pulse. As regards $B$ dependence of $v_c$, the powerlaw behavior is observed, which is in good agreement with our previous results and the sliding model.

As compared to the previous works, the present study has the advantage of the continuous sweep of the driving force to the Wigner crystal. The continuous sweep gives prominence to the transition from the dimpled to the sliding state. The quantitative analysis of the response waveform below and above $v_c$ will clarify the sliding dynamics of the Wigner crystal.

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