Evidence in Support of Dislocation-Mediated Melting of a Two-Dimensional Electron Lattice

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A sharp peak occurs in the temperature-dependent power absorbed by a two-dimensional sheet of electrons for temperatures near the melting transition when the electrons are driven parallel to the underlying helium surface with an ac voltage. The temperature at the absorption maximum is measured as a function of driving frequency, and the results are interpreted as the power absorbed by dislocations which move in response to the externally imposed stress.

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One of the more fascinating and certainly the most controversial topic in the physics of two-dimensional (2D) systems has been the nature of the melting transition. Nelson and Halperin[1] and, independently, Young[2] have extended the ideas of Kosterlitz and Thouless[3] to develop a detailed theory (KTHNY) of melting via the dissociation of dislocation pairs. This theory predicts a second-order phase transition to a hexatic liquid-crystal phase in which there exist free dislocations. Chui[4] has presented a theory of melting by the spontaneous generation of grain boundaries and found it to be energetically more favorable than the dislocation unbinding mechanism. There have also been a large number of computer simulations on systems with various interatomic potentials.[5] While some evidence is found supporting the KTHNY theory, most of the simulations exhibit a first-order phase transition. Recently, in a Monte Carlo study of a system of interacting dislocation vectors, Saito[6] found that the nature of the melting transition depended upon the magnitude of the dislocation core energy; KTHNY (grain-boundary) melting occurred for large (small) core energies.

There exists a limited amount of experimental data on the melting transition of physical 2D systems. Heiney *et al.*[7] and Rosenbaum *et al.*[8] have measured the pair correlations below and the bond-angle correlations above the melting temperature T_m in ≈ 1 monolayer of xenon on graphite. Their data agree well with the predictions of the KTHNY theory. Gallet *et al.*[9] have deduced the shear modulus μ from measurements of phonon-ripplon coupled-mode frequencies of a 2D electron lattice in the presence of a magnetic field. They observed a rapid decrease in μ as $T \to T_m$ from below and an abrupt drop in μ at T_m as predicted by the KTHNY theory.

It is desirable to find other probes to test these melting theories particularly in simple systems of continuous symmetry such as the 2D electron lattice where the substrate does not impose an orienting field and finite-size effects are not present. In this Letter we present measurements of the melting transition of a 2D electron lattice supported above a liquid-helium surface using the scattering of thermal ripplons from the electrons as an indirect probe of dislocations. The temperature at which an excess scattering peak occurs in a measurement of the low-frequency ac electron mobility[10] is measured as a function of driving frequency, and the results are analyzed in terms of losses due to the motion of free dislocations and dislocation pairs.

Our measuring technique, described in Ref. 10, involves the application of an ac driving voltage to an electrode located above one end of the 2D electron sheet. The response of the electrons to the driving voltage induces a signal on an identical electrode above the other end of the crystal and we monitor this induced signal as a function of temperature. In Fig. 1 we show the inertial, S_i, and the absorptive, S_a, components of this induced signal as a function of temperature near T_m for a drive frequency of 23 MHz. The rise in S_i as the crystal forms is related to the increasing effective mass m^* of the electrons as a dimple forms in the helium surface under each localized charge.[11,12] The absorptive signal ($\propto$ the inverse mobility) is proportional to the rate of momentum transfer from the electrons to the liquid-helium ripplons. This rate of momentum transfer is larger in the crystalline state[10,13] which accounts for the rise in S_a. In addition, the absorptive signal exhibits a sharp peak of width ~10 mK near the transition.

The absorptive signal is qualitatively identical to the temperature-dependent losses associtated with the superfluid transition in thin helium films.[14] Those data were interpreted as losses associated with the driven motion of vortex pairs

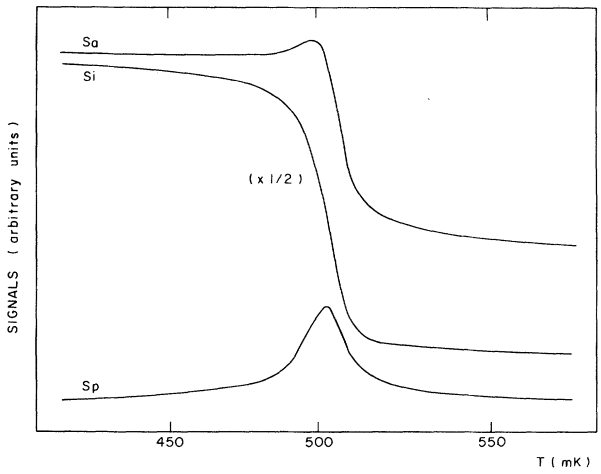

FIG. 1. The absorptive signal S_a (upper trace), inertial signal S_i (center trace), and excess scattering signal S_p (lower trace) vs temperature for a frequency of 23 MHz and temperatures near T_{KT}.

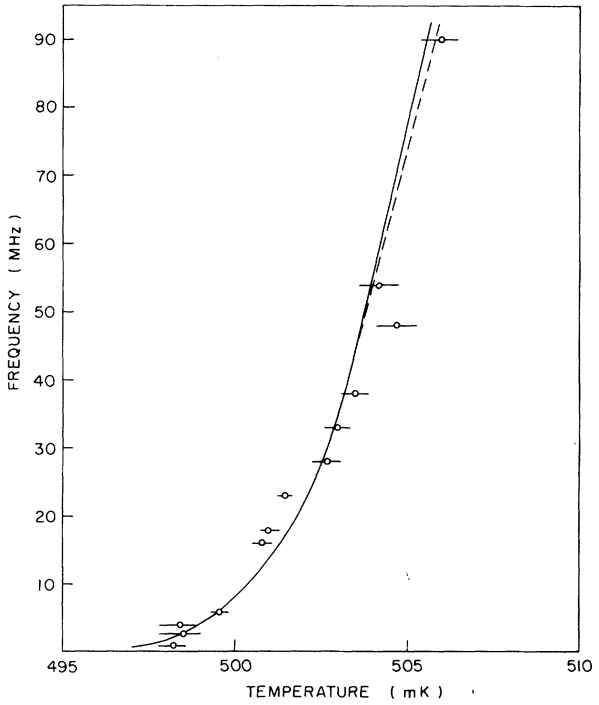

FIG. 2. Drive frequency $\omega/2\pi$ vs T_ω for $n = 5.4 \times 10^8$ cm^{-2}. The theoretical curves shown are for $\bar{E}_c = 4.92$, $D = D_0$ (solid line) and $\bar{E}_c = 4.6$, $D = 10^{-} D_0$ (dashed line).

and free vortices.[15] We use the same theory to interpret our excess absorptive peak as resulting from losses due to the driven motion of dislocations. According to the KTHNY theory, dislocation pairs exist as thermal defects in the crystalline phase. A fraction of these pairs dissociate at a temperature T_{KT} to form a bath of free dislocations above T_{KT}. Our experimental technique consists of driving a long-wavelength unilateral compressional mode of the lattice. Such a mode has a shear component associated with the relaxation of the crystal in a direction orthogonal to the compression. We suggest that the shear-induced expansion of dislocation pairs and viscous motion of free dislocations provide mechanisms for the excess absorption of energy. This absorbed energy is subsequently transmitted via the phonons to the helium bath in ripplon scattering processes. However, in order to investigate this excess absorption peak it is necessary to isolate the peak from the background change in S_a at melting.

In the absence of dislocation losses, it has been shown that both the change in S_i, ΔS_i, and the change in S_a', $\Delta S_a'$, are strongly varying functions of $\langle x^2 \rangle$, the mean square deviation of electrons from their lattice sites. The prime indicates no dislocation losses. For the large and rapidly increasing values of $\langle x^2 \rangle$ encountered at $T \geq T_{KT}$, the functional dependence of these signals on $\langle x^2 \rangle$ is nearly identical. Further, it is found experimentally[10] that the mobility in the strongly coupled regime, represented by the present measurements, has the same qualitative dependence on $\langle x^2 \rangle$ as predicted by the weak-coupling theory. We therefore assume that the changes in both S_i and the absorption in the absence of dislocation losses S_a' have the same temperature dependence in the melting region and thus differ only by a multiplicative constant.

Furthermore, the signals due to dislocation losses, S_d, and S_a' are additive since these loss processes are incoherent; $S_d + S_a' = S_a$. Thus, we set the phase of our detector to cancel the change in S_a' at melting by subtracting part of the inertial signal from S_a. The resultant signal S_p shown in Fig. 1 is proportional to S_d.

In order to insure that the electron density is the same for each data point, a measurement is taken at a standard frequency of 23 MHz both before and after data are taken at another frequency $\omega/2\pi$. All data are taken in the small-signal limit. The electron areal density n is determined from a theoretical fit of the phonon-ripplon coupled-mode spectra.[12]

The temperature of the maximum in S_p, T_ω, increases as ω is increased. In Fig. 2 this dependence is plotted as $\omega/2\pi$ vs T_ω for a density of $(5.4 \pm 0.1) \times 10^8$ cm^{-2}. Less precise data taken

at $n = 3.3 \times 10^8$ cm^{-2} gave qualitatively the same results. The experimental frequency range was limited by small signal-to-noise ratios (at low and high frequencies) resulting in difficulties in determining the proper detector phase and therefore in accurately determining T_ω.

We analyze our data with the linear response theory of Ambegaokar *et al.*[15] using the analogy between dislocations in a lattice and vortices in a helium film. In applying their theory to that of KTHNY we define a dynamic dielectric constant, $\epsilon(\omega) = \epsilon' + i\epsilon''$, which describes the softening of the lattice that occurs when free dislocations diffuse and dislocation pairs polarize in response to an applied, time-dependent stress. The time-average power per unit area absorbed by the lattice is

$$P = \tfrac{1}{2} u_{ij} C_{ijkl} u_{kl} \omega \, \mathrm{Im}[\epsilon^{-1}(\omega)], \qquad (1)$$

where u_{ij} is the strain tensor, C_{ijkl} is the bare elastic constant tensor, and the sum is over repeated indices.

There are differences between dislocations in a triangular lattice and vortices in a thin film: i.e., dislocation triplets exist, the polarization of a pair depends on the angle θ between one of the Burgers vectors and the radial vector connecting the dislocation cores, and dislocation motion is predominantly one dimensional (along the glide line).

The contribution of pairs to the dielectric constant, ϵ_p, is a function of θ, the pair separation r, and T. The dominant contribution to ϵ_p'' comes from those pairs which relax back to equilibrium in time $\tau(r, \theta) = \omega^{-1}$. To determine $\tau(r, \theta)$ we adapted the response theory of Ambegaokar and Teitel[16] to the one-dimensional motion of dislocation pairs and found the best fit to the response with a single relaxation time. Our results are $\tau(\theta = \pi/2) = r^2/8D$ and $\tau(\theta = 0) = r^2/15D$, where D is the dislocation diffusion constant. For a given value of r small values of θ are energetically favorable, and therefore we have evaluated $\epsilon_p(r, T)$ with $r = (14D/\omega)^{1/2}$. The value of $\epsilon_p(r, T)$ is obtained by integrating the recursion relations of Nelson and Halperin.

Free dislocations contribute only to ϵ''. This contribution is $\epsilon_f'' = 8\pi D n_f/\omega$, where the density of free dislocations n_f is given by[1,15]

$$n_f^{-1} = 2\pi\xi_+^2 = 2\pi f^{-1} a_0^2 e^{2l^*}. \qquad (2)$$

Here a_0 is a lattice spacing and we treat f as a fitting parameter. The value for $l^*(T)$ is obtained from the recursion integration.

The power absorbed is calculated as a function of temperature with use of Eq. (1) with $\epsilon = \epsilon_p + \epsilon_f$. For an external stress applied at a frequency $\omega/2\pi$, we find that the theoretical power absorption has a sharp maximum at a temperature T_ω. The curve shown in Fig. 2 is a plot of the excitation frequencies versus the temperatures T_ω. This theoretical curve is obtained with the parameters $\bar{E}_c = E_c/k_B T_{KT} = 4.92$, $T_{KT} = 490.4$ mK, $D = D_0 = \frac{1}{2}\omega_m a_0^2$, $f = 1$ (solid curve) or $\bar{E}_c = 4.6$, $T_{KT} = 491.5$ mK, $D = 10^{-1} D_0$, $f = 1$ (dashed curve).[17] The two fits are identical at low frequencies. Here E_c is the dislocation core energy and ω_m is the largest transverse phonon frequency of the lattice. Equally good fits are given by the parameters $\bar{E}_c = 5$, $T_{KT} = 488.7$ mK, $D = D_0$, $f = 1$ and $\bar{E}_c = 5.2$, $T_{KT} = 486.3$ mK, $D = D_0$, $f = 5$. These values of E_c are ~5% to 20% less than the finite-temperature (shear-modulus renormalized) values of E_c from Fisher, Halperin, and Morf[18] and Morf,[19] but are ~10% greater than the larger (renormalized) core energy used by Saito.[6]

The theoretical linewidths of the absorption peaks increase with increasing ω and for $D = D_0$ ($D = 10^{-1} D_0$) are in the range of 3 to 10 (5 to 15) mK. Our experimental linewidths are 15–20 mK and are nearly frequency independent. The experimental linewidths are probably broadened by the reduced electron density at the edges of the experimental cell and possibly from our background subtraction procedure.

The results presented here represent the first measurements of dynamic processes occurring near melting in a 2D lattice. The ω vs T dependence of the excess peak is explained with the theory of dislocation-mediated melting. The model of grain-boundary melting[4] predicts a dramatic increase in the total number of dislocations at melting, and one would expect an abrupt change in the scattering at the melting transition contrary to our observations. We believe that the results presented here, along with the shear-modulus studies at melting,[9] provide strong support for dislocation-mediated melting of the two-dimensional electron lattice supported above a liquid-helium substrate.

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