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Dimples due to Dislocations at the Superfluid/Solid Interface of ^{4}He

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On vicinal planes the surface stiffness is quite anisotropic and a crystal defect, terminating at the interface, is predicted to produce a 10...50 *nm deep dimple with macroscopic lateral extent (up to a few mm). We have searched for such depressions using high resolution interferometry. Sometimes our measured interferograms of the superfluid/solid interface display unexpectedly large dimples. The volume and shape of the observed objects suggest that these dimples are caused by bundles of about* 10 *dislocations.*
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1. INTRODUCTION

Helium crystals provide unique model systems for investigations of surface phenomena in solids. In ^{4}He crystals, contrary to classical substances, relaxation into the true thermodynamical equilibrium shape takes place very rapidly owing to the good thermal conductivity of the surrounding superfluid phase. Moreover, since the latent heat of fusion is almost zero in ^{4}He, a study of the intrinsic properties of the liquid/solid interface, without heat or mass diffusion effects, becomes possible.

^{4}He crystals may contain facets (atomically smooth faces) in their equilibrium shape. For a perfect facet, the growth coefficient K is exactly zero: It can grow only owing to fluctuational mechanisms which enable the nucleation of new atomic layers. Since thermal nucleation of layers, dominant at higher temperatures, fails to explain the observed increase of K towards lower temperatures,[1] another mechanism has to be involved. One explanation is that spiral growth takes place along dislocation lines, penetrating the crystal. These imperfections are expected to form definite traces on the surface, *viz.*, dimples whose observation using high-resolution interferometric techniques should be possible. Recently, it has been shown that such interferometric techniques can be applied also in investigations at ultra low temperatures.[2]

2. THEORETICAL BACKGROUND

The equilibrium shape of any crystalline matter is controlled by its surface stiffness γ. In crystals, γ can be described by means of a tensor with two principal components, $\gamma_{\|}$ and $\gamma_{\perp}$. One of these components, $\gamma_{\|}$, becomes very small at the so called *vicinal surfaces, i.e.*, in the vicinity to the facets. The effects, caused by dislocations in the crystal, are thus enhanced on these slightly tilted vicinal surfaces which are considered to be built of terraces of atomic layers, limited by steps. The free energy of a vicinal surface can be written as a function of the step density n as[3]

$$E(n) = E_o + \beta n + \frac{\delta}{6} n^3 \tag{1}$$

where E_o is the surface energy of a facet without steps, β is the step energy and $\delta = \gamma_{\|}/\tau$ is a parameter of the interaction between steps; τ is the inclination angle of the vicinal surface.

A screw dislocation, terminating on the surface of a crystal, forms a dimple on the liquid/solid interface, like a vortex line on the free surface of the superfluid. In a macroscopic approach, when the length scales under consideration are much larger than the distance between steps $d = a/\tau$, where a is the step height, one can use the following equation[4]

$$\delta \tau \zeta''_{xx} + \frac{\beta}{\tau} \zeta''_{yy} - \frac{\mu}{8} \frac{b^2}{\pi^2} \frac{1}{r^2} - (\rho_s - \rho_l) g \zeta = 0 \tag{2}$$

in order to find the shape of the dislocation dimple on the crystal surface. Note that in the third term there is a factor ($-\mu b^2/8\pi^2$) instead of $\rho_l \hbar^2/2m^2$, which corresponds to the "vortex" case in Ref. 4. In Eq.(2), $\zeta(x, y)$ is the interface profile, μ is the modulus of rigidity, b denotes the Burger's vector of the dislocation, and ρ_l and ρ_s are the densities of the liquid and solid phases, respectively. The analytic solution of Eq.(2) can be obtained using 2-dimensional Fourier transformation (see Ref. 4). The extent of the defect-induced depression on the liquid/solid interface is, in general, determined by two capillary lengths, $l_{\|} = \sqrt{\delta\tau/(\rho_s - \rho_l)g}$ and $l_{\perp} = \sqrt{\beta/(\rho_s - \rho_l)g\tau}$, which correspond to the two principal components,

$\gamma_{\parallel}$ and $\gamma_{\perp}$, of the surface stiffness tensor ($l_{\perp} >> l_{\parallel}$). For the depth of the dimple, caused by a single dislocation on the crystal surface, Eq.(2) yields $\zeta_o \approx \mu b^2/16\pi^2(1/\sqrt{\beta\delta})ln(\tau l_{\parallel}/a)ln(l_{\parallel}/\tau a)$. Using the values[5] β = 0.011 erg/cm^2, δ = 0.5 erg/cm^2, measured at $T \leq 0.1$ K, and taking τ = 10^{-2}, one obtains for the dimple depth ζ_o = 60 nm, which is well within the resolution of our interferometric techniques.[2]

3. EXPERIMENTAL TECHNIQUES

In our experiments we have employed an optical interferometer (similar to that used in the experiments described in Ref. 2) built into a small dilution refrigerator, capable of achieving temperatures down to 40 mK. Our cell is a copper cylinder of 40 mm in diameter, capped from both ends by fused silica windows. The lower window is an optical wedge of high quality; the upper surface (with a reflection coefficient of $R \approx 10^{-4}$) of the wedge is used as a reference plane. Laser light (He-Ne, λ = 632.8 nm), guided into the cryostat via an optical fiber, is expanded to a collimated beam of 5 mm in diameter and passed through the cell. Coherent reflections from the liquid/solid interface and from the reference plane create an interference pattern. The interferograms were captured by a cooled CCD camera (Photometrics STAR 1 - system) inside the 4-K vacuum can, operated remotely in a slow-scan mode.

Our crystals were grown at about T = 0.9 K, by compressing the superfluid phase inside the cell; care was taken not to increase the linear velocity of the interface above 10^{-4} cm/sec while growing the crystal. This was accomplished by admitting a controlled ^{4}He gas flow from the room temperature supply via the filling capillary. In order to have the correct parallel orientation of the basal (0001) plane with respect to the reference flat, a special nucleator technique was employed.[6]

4. RESULTS

Fig. 1 depicts an interferogram of a ^{4}He crystal measured at T = 0.5 K; the inclination of the imaged vicinal surface equals $\tau = 5{\cdot}10^{-3}$ rad. The adjacent fringes are contours of the equal height of the liquid/solid interface above the slightly tilted reference wedge (inclination about 10^{-2} rad with respect to the gravitational horizon). One can see from the interferogram that the liquid/solid interface is not uniform but distorted by an elongated depression, consisting of two separate formations tightly joined together.

The two length scales, governing the size of the formations, can be found directly from the interferogram. We obtain for the distance, characterizing

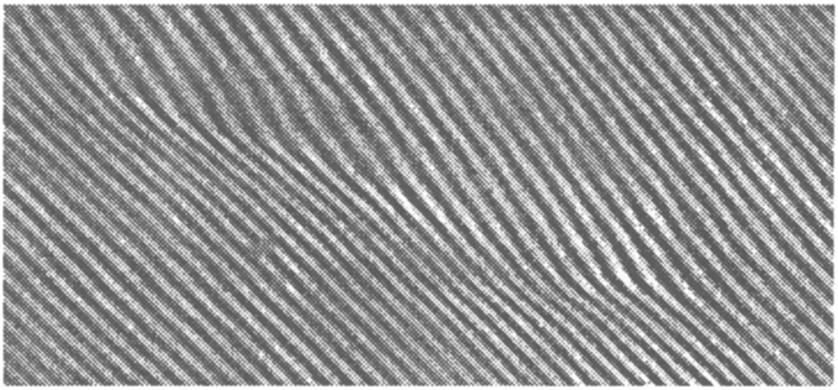

Fig. 1. Interferogram of a dimple on the liquid/solid interface of ^{4}He caused by a bunch of dislocation lines; $T \approx 0.5$ K. The displayed area is 3.0×1.4 mm^2.

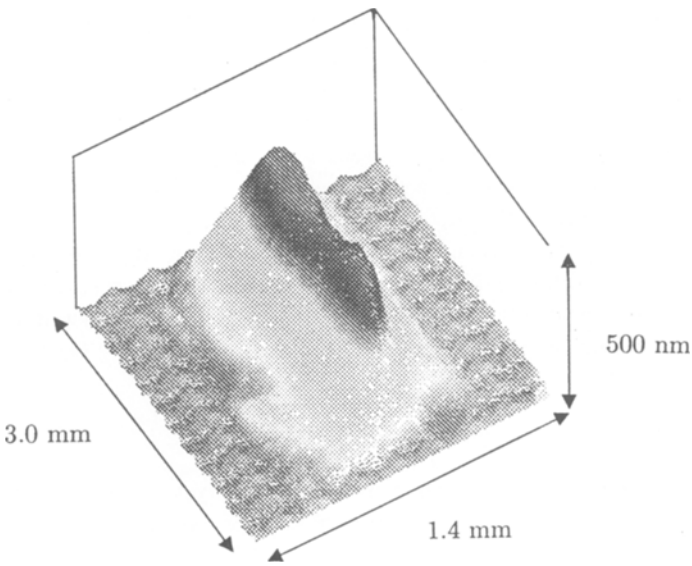

Fig. 2. Dimple profile on the crystal surface (shown as inverted) obtained from the interferogram presented in Fig. 1.

the extent of the defect across the steps, $\Delta_{\parallel} \approx 0.06$ cm, and for the respective distance along the steps $\Delta_{\perp} \approx 0.28$ cm. These values have to be compared with the corresponding capillary lengths (see Sec. 2), $l_{\parallel} = 0.04$ cm and $l_{\perp} = 0.4$ cm, calculated using the values of $\beta = 0.011$ erg/cm^2, $\delta = 6$ erg/cm^2 (obtained by extrapolation of the data in Ref. 5), and $\tau = 5{\cdot}10^{-3}$. Thus, the ratio of two measured length scales, $\Delta_{\perp}/\Delta_{\parallel} \approx 5$, is not far from the theoretical value, $l_{\perp}/l_{\parallel} = 10$.

A reconstructed surface profile of the distortion on the interface is presented in Fig. 2. It shows that the dimple, almost 500 nm in depth, has a clear double-well structure. The volume of dimples on the liquid/solid interface, caused by dislocations, can be estimated by direct integration of Eq.(2), which yields $V_D = 3{\cdot}10^{-8}$ cm^3 for one isolated line. Comparing the calculated value of V_D with the measured volume of the dimple in Fig. 2, we conclude that the observed depression corresponds to a bundle of about 10 dislocation lines.

So far, we have not been able to resolve dimples from single dislocation lines. Experimentally, it should be possible to observe such traces of isolated defects on the crystal surface. This would provide a local probe on the surface stiffness which presumably could be used to verify the recently observed increase of the surface stiffness at small angles.[7]

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