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Surface state electrons on quench-condensed hydrogen films as a surface probe

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The surface of quench-condensed hydrogen films was studied employing conductivity measurements of surface state electrons (SSE). The surface quality of the films could be drastically improved by thermal annealing. The absence of any residual gas above the surface was found to be essential for an effective annealing process. The SSE conductivity reached values comparable to those obtained on bulk hydrogen crystals. Adsorbing small amounts of helium onto the surface led to pronounced conductivity oscillations, which are ascribed to a layering of the helium film. This has previously been observed only on bulk hydrogen. The positions of the conductivity maxima agree with those expected from previously published values of the binding energy of helium on bulk solid hydrogen.

1. Introduction

Surface state electrons (SSE) on solid hydrogen have been a field of continuing activity over the past years [1]. On the one hand they can be used as an extremely sensitive probe of surface disorder and surface excitations by studying their transport properties. On the other hand there is major interest in the electron system itself, since SSE (as observable on helium, neon, and hydrogen surfaces) represent an in principle "clean" and well-defined two-dimensional electron system. Studies at high electron densities, where correlation and quantum effects become important, can lead to new insights into the behavior of 2D electrons at a state comparable to that in MOSFET structures, under even better controlled conditions. There have already been a number of experiments looking at SSE on solid substrates, that is, on thin neon crystals [2] and bulk hydrogen crystals [3], as well as on quench-condensed hydrogen films [4,5].

The electron density is proportional to the applied electric holding field. Since the voltage that can be applied in a cryogenic environment is limited, it appears rather important for further investigations to prepare these substrates as thin films in order to reach a high electron density. Quench condensation is one of the methods to prepare thin films. In general, however, these films are disordered and their surface is rough, so that SSE are strongly localized. In the present study we show, using the conductivity of the SSE as a surface probe, that the surface of thin (2 μm) quench-condensed hydrogen films can be made sufficiently smooth after a proper annealing procedure to provide a useful substrate for studies of

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2D electron systems. On these annealed surfaces we succeeded in observing the layering of a helium film, which has previously been observed only on smooth crystalline bulk surfaces [6,7].

2. Experimental and results

The hydrogen films were quench-condensed onto a 0.2 mm thick float glass plate kept at 1.8 K during the condensation process, which was mounted onto two concentric electrodes. These were used to measure the AC conductivity of the SSE employing the Sommer–Tanner method [8]. The electron density was kept constant at $\sim 5 \times 10^8$ cm^{-2}. Details of the experimental setup and procedure are given elsewhere [4]. In order to obtain a high conductivity signal it was necessary to keep the condensation rate sufficiently low (~ 1 μm/h).

After the condensation (typical film thickness 2 μm) we annealed the film. The improvement of the surface quality during annealing was monitored by measuring the SSE conductivity, as shown in fig. 1. No conductivity signal was observed on the freshly prepared film up to an annealing temperature of 3.6 K, meaning that the initial surface was quite rough. Above 3.6 K the electron conductivity grew rapidly. After reaching

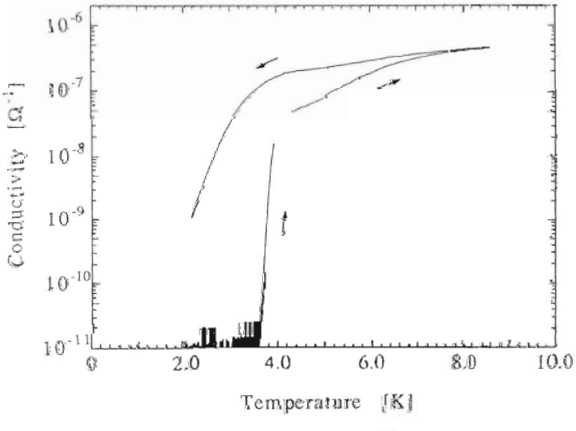

Fig. 1. Behavior of the SSE conductivity during the first annealing process after the quench condensation of the hydrogen substrate. Arrows indicate the direction of the chronological development.

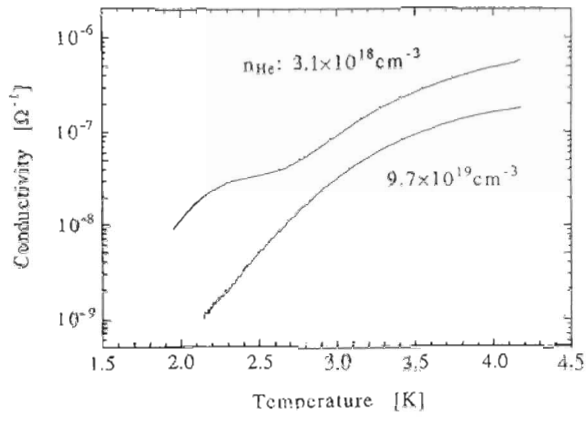

Fig. 2. Temperature dependence of the SSE conductivity for different helium gas atom densities n_{He} in the cell. The hydrogen film is the same as that of fig. 1. The film was annealed with helium gas ($n_{He} = 9.7 \times 10^{19}$ cm^{-3}) in the cell.

8 K the system was cooled down again. Fig. 1 shows that the annealing procedure had obviously improved the surface quality quite strongly. However, even after the annealing, the SSE conductivity still shows a thermal-activation type temperature dependence between 2 and 4 K. The magnitude of this conductivity change gives a measure of the surface quality as discussed in previous work [4].

The annealing process shown in fig. 1 was carried out with helium atoms in the cell. Before charging the film with electrons emitted from a heated tungsten filament, a small amount of helium gas was admitted to the cell in order to slow down the electrons and thus prevent them from penetrating the hydrogen film. Fig. 2 shows the temperature dependence of the SSE conductivity on an annealed film with two different amounts of helium gas in the cell. For the lower helium gas atom density (upper trace), an oscillation of the SSE conductivity is observed, superimposed on the overall temperature dependence of the thermal-activation type. We ascribe this oscillation to a layering of helium on the solid hydrogen substrate, as discussed later.

The annealing process was carried out also without helium. Fig. 3 shows the temperature dependences of the SSE conductivity (after annealing at only 4 K) for several different helium

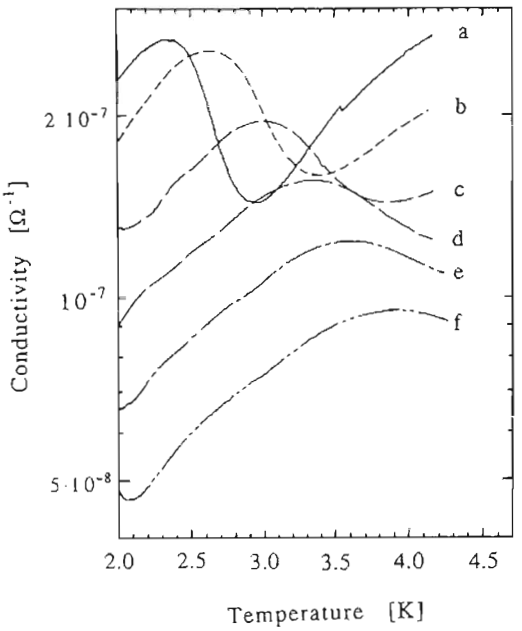

Fig. 3. Temperature dependence of the SSE conductivity on a hydrogen film annealed without helium in the cell. Labels (a)–(f) correspond to different helium gas atom densities as follows: (a) 0.51; (b) 1.1; (c) 2.4; (d) 4.6; (e) 6.7; (f) 9.7 ($\times 10^{19}$ cm^{-3}).

gas atom densities. Trace (a) shows a far more prominent oscillation compared to the upper trace of fig. 2. The oscillations in the conductivity get progressively smeared out with increasing gas atom density. The conductivity change between 2 and 4 K for the highest gas atom density (trace (f)), is about an order of magnitude smaller than for the lower trace in fig. 2, measured with the same gas density. Assuming a thermally activated behavior of the SSE conductivity in the temperature regime, where the oscillations ascribed to a layering of the helium on the hydrogen surface can be neglected, one can extract an activation energy for the conductivity [4]. The data shown yield activation energies of ~ 15 K for the hydrogen film annealed under helium atmosphere (fig. 2) and 5 K for the film in fig. 3, which was annealed when residual gas above the hydrogen surface was pumped out. These facts suggest that the surface quality for the hydrogen film of fig. 3, showing more pronounced layering oscillations and less temperature dependence, is a lot better than for that of fig. 2.

3. Discussion

As seen from figs. 2 and 3, the surface quality could be improved more by annealing without helium than with helium in the cell. In fact, the absence of gas above the hydrogen surface was found rather crucial for the annealing process. We attribute this behavior to a major portion of the surface annealing being due to selective evaporation of hydrogen atoms from protrusions. In the presence of helium they are scattered back onto the surface by the gas atoms, rendering the annealing process a lot less efficient.

The present experimental results show that the surface of the quench-condensed hydrogen film can be made smooth enough to show a pronounced helium layering effect. The conductivity maximum is to be attributed to the completion of the first monolayer [6,7]. Layering effects are expected to be smeared out to a large extent already for the second layer at the temperatures of the experiment [6] consistent with the observation. Plotting the SSE conductivity versus the chemical potential of the helium gas with respect

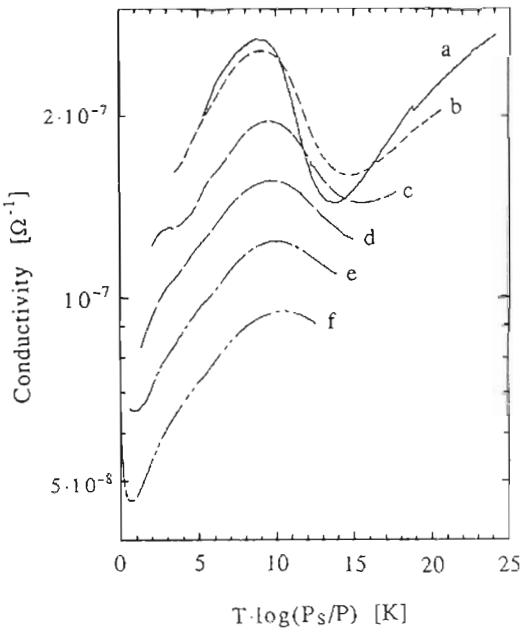

Fig. 4. Data of fig. 3 versus $T \log p_s/p$, where p_s is the saturated vapor pressure of helium and p is the actual pressure of helium in the cell. Labels are the same as in fig. 3.

to the bulk liquid T log p_s/p (where $p_s(T)$ is the saturated vapor pressure and p the actual gas pressure of helium in the cell), fig. 4 shows the consistency of the layering interpretation. The maxima are seen to correspond to each other for the different runs. The binding energy of helium on solid hydrogen amounts to 9 K for the first layer. A structure in the conductivity which might correspond to the completion of the second layer can also be seen around a binding energy of 2.7 K. These energies are in good agreement with previously published values [6,7,9] (there have been measurements of lower binding energies for helium on hydrogen by Shirron and Mochel [10], suggesting to interpret the conductivity oscillations in SSE experiments as half-layer effects; however, we do not see any reason why the SSE conductivity should show maxima at half-layer intervals).

4. Conclusions

To summarize we have succeeded in reproducibly preparing thin (a few μm thickness) solid hydrogen films by quench condensation and subsequent thermal annealing. They show a high SSE conductivity comparable to that on bulk solid hydrogen. The surface annealing was found to be a lot more efficient when no residual gas was present above the surface. This is interpreted by selective evaporation from protrusions playing a major role for the annealing process. The layering of helium films adsorbed onto the hydrogen surface, which so far was observed only on bulk crystals, is observed here for the first time on a thin film. The positions of the conductivity maxima due to completion of the first and second monolayer of helium agree with those expected from previously published values of the binding energies of helium on hydrogen.

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