thews, C. E. Max, K. G. Tirsell, and other colleagues in the Livermore Laser Fusion program.

This work was performed under the auspices of the U. S. Department of Energy, Contract No. W-7405-ENG-48.

[1]R. C. Malone, R. L. McCrory, and R. L. Morse, Phys. Rev. Lett. 34, 721 (1975).

[2]B. H. Ripin *et al.*, Phys. Rev. Lett. 34, 1313 (1975).

[3]J. S. Pearlman and J. P. Anthes, Appl. Phys. Lett. 27, 581 (1975).

[4]B. Yaakobi and A. Nee, Phys. Rev. Lett. 36, 1077 (1976).

[5]W. C. Mead *et al.*, Phys. Rev. Lett. 37, 489 (1976).

[6]F. C. Young *et al.*, Appl. Phys. Lett. 30, 45 (1977).

[7]B. Yaakobi and T. C. Bristow, Phys. Rev. Lett. 38, 350 (1977).

[8]P. M. Campbell, R. R. Johnson, F. J. Mayer, L. V. Powers, and D. C. Slater, Phys. Rev. Lett. 39, 274 (1977).

[9]R. Benattar, C. Popovics, R. Sigel, and J. Virmont, Phys. Rev. Lett. 42, 766 (1979).

[10]M. D. Rosen *et al.*, Phys. Fluids 22, 2020 (1979).

[11]J. A. Stamper *et al.*, Phys. Rev. Lett. 26, 1012 (1971); for an extensive review see J. A. Stamper, U. S. Naval Research Laboratory Report No. 3872, 1978 (unpublished).

[12]D. W. Forslund, J. Geophys. Res. 75, 17 (1970); R. Bickerton, Nucl. Fusion 13, 457 (1973).

[13]E. J. Valeo and I. R. Bernstein, Phys. Fluids 19, 1348 (1976).

[14]W. W. Simmons *et al.*, Appl. Optics 17, 999 (1978).

[15]K. G. Tirsell, H. N. Kornblum, and V. W. Slivinsky, Bull. Am. Phys. Soc. 23, 807 (1978).

[16]A change in the absorption mechanism has not been ruled out. Anomalous absorption in the far underdense plasma would shift the energy flow away from the overdense plasma toward more energetic plasma blowoff. For example, a buildup of ion-acoustic turbulence with increased laser intensity might simultaneously increase inhibition and cause anomalous absorption. R. J. Faehl and W. L. Kruer, Phys. Fluids 20, 55 (1977); W. M. Manheimer, D. G. Colombant, and B. H. Ripin, Phys. Rev. Lett. 38, 1135 (1977).

[17]G. B. Zimmerman, Lawrence Livermore Laboratory Report No. UCRL-74811, 1973 (unpublished).

[18]For a discussion of the physics modeling in these simulations, see Ref. 10.

Surface Diffusion by an Atomic Exchange Mechanism

John D. Wrigley and Gert Ehrlich

Coordinated Science Laboratory, Department of Physics and Department of Metallurgy, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

(Received 31 December 1979)

On Ir(110), tungsten adatoms move preferentially across [1$\bar{1}$0] channels rather than along them, as observed on other channeled planes. The jump mechanism underlying this anomalous behavior has been tested in an atom probe. It is found that after cross-channel motion, an iridium adatom is left on the iridium surface rather than the tungsten originally deposited. These observations provide the first experimental evidence for atomic diffusion on a metal by exchange of the adatom with an atom from the substrate.

In the past, it has generally been assumed that atomic diffusion on metals occurs by hopping over the surface. Observations of single metal atoms on channeled planes such as (211) of tungsten and (110) of rhodium[1] fit in well with this view. Migration on these surfaces is one dimensional (1D); as expected from the atomic arrangement of such planes, atoms move only in the direction of the surface channels. Recently, however, quite a different behavior has been found on some face-centered-cubic metals. On Pt(110), modeled in Fig. 1, Bassett and Webber[2] observed 2D diffusion of platinum and iridium atoms, with frequent movements across as well as along the [1$\bar{1}$0] rows. On iridium (110), diffusion of iridium and tungsten atoms occurs preferentially across the channels.[3] Cross-channel motion of atoms may be visualized[2,4] in two different ways: (1) via atomic jumps *over* the rows of lattice atoms forming the ridges, which *a priori* appear more unlikely than jumps along the channels; or (2) by an exchange process. In the latter, the adatom takes the place of a lattice atom in the side of the channel; it is the displaced lattice atom that continues the diffusion. We report here the first experimental evidence that cross-channel diffusion does, in fact, occur by an exchange mechanism.

The idea underlying our experiments is simple. Consider what happens when a foreign adatom,

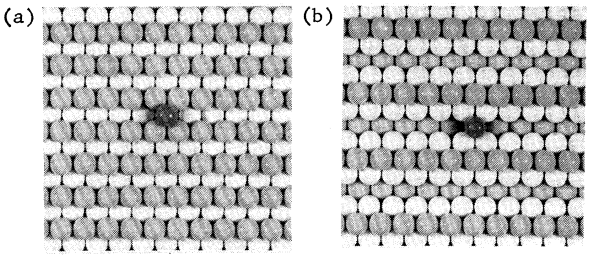

FIG. 1. Hard-sphere model of the (110) plane of an fcc lattice. Outermost lattice layer in grey, second layer in white, adatom in dark grey. (a) Ideal 1×1 surface. (b) A reconstructed 1×2 surface, obtained by removal of alternate $[1\bar{1}0]$ rows.

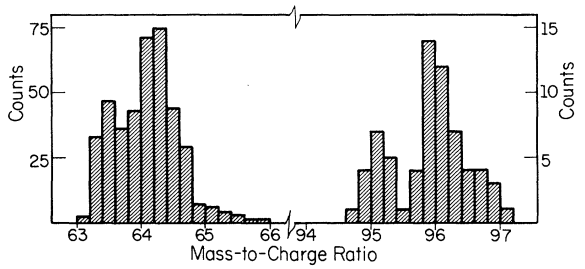

FIG. 2. Calibration of atom probe on iridium substrate at $T<50$ °K. Background pressure $<2\times10^{-10}$ mm. Peak at left arises from Ir^{+3}, that at right from Ir^{+2}.

such as tungsten, is deposited on a (110) plane of iridium. In cross-channel motion by a hopping process, the tungsten atom just jumps from one channel to the next. However, if exchange is the dominant mechanism, then after diffusion an iridium atom rather than the original tungsten should appear in the adjacent channel. To distinguish between the two mechanisms it is sufficient to determine the chemical identity of the adatom after cross-channel motion. This is now possible in the atom probe.[5] We have carried out such measurements for the diffusion of tungsten atoms on the (110) plane of iridium.

In our instrument,[6] the iridium surface formed by field evaporation below 50 °K can be photographed with atomic resolution, as in a simple field-ion microscope. From the overall dimensions of the (110) plane, and the number of $[1\bar{1}0]$ rows on it, we conclude that the distance from one row to the next is roughly twice as large as in the bulk. An atomic arrangement conforming to such a channel spacing is indicated in the model in Fig. 1(b). It is worth noting that the structure of Ir(110) produced by field evaporation appears to agree with that proposed for macroscopic (110) planes of iridium on the basis of low-energy electron-diffraction (LEED) measurements.[7]

To use the atom probe for determining the chemical identity of atoms diffusing on Ir(110), it is first necessary to calibrate the mass scale. In our experiments, all under ultrahigh-vacuum conditions, this was done by determinations on the iridium substrate (Fig. 2), and on adatoms. For the latter, iridium and subsequently tungsten atoms were evaporated in separate experiments onto an iridium sample at $T<50$ °K. Without ever warming the surface, the atoms were pulse desorbed, and their time of flight was determined. It should be noted that in each experiment only a single atom was placed on the (110) plane; its presence on (110) after deposition was verified by field-ion microscopy at the detector. That the atom had indeed been removed by the field pulse was also checked after each charge-to-mass determination. The results of these measurements are shown in Fig. 3; there data on all charge states observed for a given chemical entity are combined under the same AMU bin. The separation between the iridium and tungsten distributions observed with adatoms is as expected from the calibration on the iridium substrate, and it is clear that iridium adatoms can be readily distinguished from tungsten adatoms in our atom probe.

The results of the crucial experiments are juxtaposed with the calibrations in Fig. 3. In these experiments, a single tungsten atom is deposited on the (110) plane. The surface is then

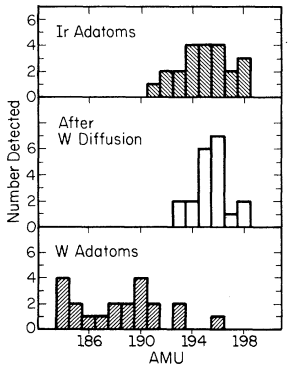

FIG. 3. Atom-probe measurements on single adatoms pulse desorbed from iridium. Atomic-mass data (AMU) obtained by combing information on all charge states detected on pulsing. Top: Calibration on iridium atoms. Bottom: Calibration on tungsten atoms. In both calibrations, atoms are deposited on surface at 50 °K, and pulsed off without ever warming the substrate. Center: Adatoms detected after depositing tungsten atom on Ir(110), and warming to allow a cross-channel jump.

warmed to ≈ 270 °K in order to initiate a cross-channel jump. After cooling to below 50 °K, the atom appearing in the adjacent channel is pulse desorbed and its charge-to-mass ratio is measured. It is apparent from the data in Fig. 3 that after a cross-channel event, an iridium atom rather than the tungsten atom initially deposited on the surface is present in the adjacent channel.

Our measurements thus lead us to conclude that for tungsten atoms on Ir(110), cross-channel motion occurs by exchange of the tungsten adatom with an atom from the substrate, presumably from the protruding rows forming the channels. If this is indeed what happens, then we should also expect to find a tungsten atom incorporated in the substrate on analyzing the first lattice layer. These measurements have been done. After cross-channel motion of a tungsten adatom and subsequent field evaporation of the adatom remaining on the surface we do indeed find tungsten incorporated in the lattice. In a comparable number of blank runs on the substrate, tungsten was never detected.

Several other observations, which will be reported fully elsewhere, also support the conclusion that cross-channel motion of tungsten atoms on the (110) plane of iridium occurs by exchange with lattice atoms. We presume that a similar mechanism accounts for channel crossings in self-diffusion on Ir(110), and also on Pt(110). It is of interest that for both iridium[8] and platinum,[9,10] LEED measurements on (110) yield a 1×2 pattern suggesting a channel spacing twice the normal value. In contrast, for rhodium (110), no rearrangement is indicated by LEED data,[11,12] and neither are there any indications of cross-channel diffusion.[13] This suggests that the forces responsible for the restructuring of the (110) plane may also favor cross-channel motion by an exchange mechanism.

We are indebted to R. S. Chambers for expert assistance with the atom probe. The work reported here was supported by the National Science Foundation under Grant No. DMR 77-23723; the Coordinated Science Laboratory is operated under Contract No. N00014-79-C-0424 from the Joint Services Electronics Program.

[1]For reviews of early measurements, see G. Ehrlich, Surf. Sci. 63, 422 (1977) or D. W. Bassett, Surf. Sci. 53, 74 (1975).

[2]D. W. Bassett and P. R. Webber, Surf. Sci. 70, 520 (1978).

[3]J. W. Wrigley and G. Ehrlich, to be published.

[4]T. Halicioglu, Surf. Sci. 79, L346 (1979).

[5]E. W. Müller and T. T. Tsong, *Field Ion Microscopy* (American Elsevier, New York, 1969).

[6]For a general description of our atom probe, see R. S. Chambers and G. Ehrlich, J. Vac. Sci. Technol. 13, 273 (1976). More details are given by R. S. Chambers, University of Illinois at Urbana-Champaign, Coordinated Science Laboratory Report No. R-702, 1975 (unpublished).

[7]C. -M. Chan, K. L. Luke, M. A. Van Hove, W. H. Weinberg, and E. D. Williams, J. Vac. Sci. Technol. 16, 642 (1979).

[8]K. Christmann and G. Ertl, Z. Naturforsch. A 28, 1144 (1973).

[9]H. P. Bonzel and R. Ku, J. Vac. Sci. Technol. 9, 663 (1972).

[10]C. M. Comrie and R. M. Lambert, J. Chem. Soc. Faraday Trans. 1. 72, 1659 (1976).

[11]C. W. Tucker, J. Appl. Phys. 37, 4147 (1966).

[12]R. A. Marbrow and R. M. Lambert, Surf. Sci. 67, 489 (1977).

[13]G. Ayrault and G. Ehrlich, J. Chem. Phys. 60, 281 (1974).

Ripplons, ^{3}He, and Heat Conduction on the Surface of Superfluid ^{4}He

I. B. Mantz, D. O. Edwards, and V. U. Nayak
Physics Department, Ohio State University, Columbus, Ohio 43210
(Received 11 December 1979)

A gradient in the concentration of adsorbed ^{3}He, produced by a current of ripplons, has been observed in heat-conduction measurements on the surface of superfluid ^{4}He. The ^{3}He spreading pressure and ^{3}He-ripplon collision rate have been determined from the data.

According to the phenomenological theory of Andreev and Kompaneets[1] the free surface of superfluid ^{4}He is governed by a two-dimensional (2D) version of the classic Landau theory of superfluidity. "Ripplons" (quantized capillary waves) are the elementary excitations of the sur-

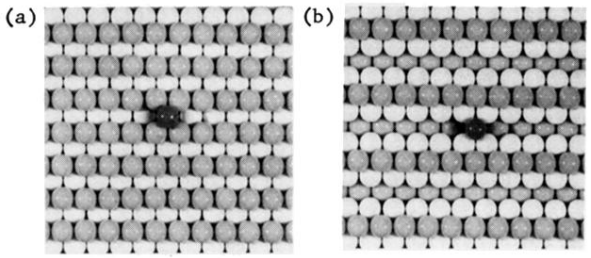

FIG. 1. Hard-sphere model of the (110) plane of an fcc lattice. Outermost lattice layer in grey, second layer in white, adatom in dark grey. (a) Ideal 1×1 surface. (b) A reconstructed 1×2 surface, obtained by removal of alternate $[1\bar{1}0]$ rows.