

Fig. 3. Zonal velocity (\diamond) and atmospheric rotation period (\bigcirc) as a function of latitude for longlived features in the atmosphere of Neptune. The upper axis shows atmospheric rotation periods (7). The lower axis indicates eastward velocity relative to a uniform rotation period of 16.05 hours, the radio rotation period (13). Points indicated by squares were obtained from ground-based observations; all other points were derived from spacecraft images. Some features were measured at two different latitudes. The points are connected by lines merely to clarify the diagram; higher resolution data may reveal additional structure.

many rotations over the time of extrapolation. For instance, S54 made 15.19 rotations while S22 made 13.11 rotations in the same 10-day interval.

Wind is perhaps the most fundamental variable in dynamic meteorology, yet there is no unified theory that accounts for the wind speeds observed in all planetary atmospheres. Two decades ago, the importance of planetary rotations in organizing planetary flows was not anticipated. Over the years Voyager wind observations revealed many surprises, including the high-velocity, localized winds in the midst of Jupiter's longlived large features (9), the high wind speed at Saturn's equator relative to the interior (15), and the dominance of east-west winds at Uranus despite that planet's peculiar orientation (14). The resemblance to the other giant planets is probably just the first of Neptune's surprises. The only sure lesson in the science of comparative planetology is humility.

REFERENCES AND NOTES

- B. A. Smith, H. J. Reitsema, S. M. Larson, Bull. Am. Astron. Soc. 11, 570 (1979); R. J. Terrile and B. A. Smith, *ibid.* 15, 858 (1983); J. N. Heasley, Publ. Astron. Soc. Pac. 96, 767 (1984); _____, C. B. Pilcher, R. R. Howell, J. J. Caldwell, *learus* 57, 432 (1984); B. A. Smith, in Uranus and Neptune, J. T. Bergstralh, Ed. (NASA Conf. Publ. 2330, National Aeronautics and Space Administration, Houston, 1984), pp. 213–223; M. J. S. Belton and R. Terrile, *ibid.*, pp. 327–347; H. B. Hammel and M. W. Buie, *learus* 72, 62 (1987).
- 2. H. B. Hammel, thesis, University of Hawaii at Manoa (1988); *Icarus* 80, 14 (1989).
- 3. _____, Science 244, 1165 (1989).
 4. D. Slavsky and H. J. Smith, Astrophys. J. 226, L49 (1978); H. J. Smith and D. Slavsky, Bull. Am. Astron. Soc. 12, 704 (1980); M. J. S. Belton, L.

Wallace, S. Howard, *Icarus* **46**, 263 (1981); R. H. Brown, D. P. Cruikshank, A. T. Tokunaga, *ibid.* **47**, 159 (1981).

- 5. H. B. Hammel et al., Icarus 79, 1 (1989)
- H. B. Hammel and J. Harrington, in preparation.
 A rotation period is defined as the time interval
- A rotation period is defined as the time interval between successive crossings of a reference meridian that is tied to a nonrotating (inertial) coordinate system.
- 8. The ground-based latitudes were originally measured in a planetocentric coordinate system and have been converted to a planetographic system. Planetocentric latitude is the elevation angle of a line from a planet's center relative to the planet's equatorial plane. Planetographic latitude is the elevation angle of the normal to the planet's surface relative to the planet's equatorial plane. The two latitudes are identical for a spherical body; Neptune's oblateness leads to a difference of less than 1° between the two systems.
- B. M. Peek, *The Planet Jupiter* (Faber and Faber, London, revised ed., 1981), chap. 9; B. A. Smith and G. E. Hunt, in *Jupiter*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1976), pp. 564–585; B. A. Smith et al., *Science* 204, 951 (1979); B. A. Smith et al., *ibid.* 206, 927 (1979).
- 10. The phase angle (the angle between the sun, the planet, and the spacecraft) was 15°.
- 11. In our measurements we used raw images in order to

avoid artifacts that are introduced by image processing.

- ing.
 12. We used the program NAV, which was developed by G. Yagi at the Multimission Image Processing Laboratory (MIPL), Jet Propulsion Laboratory, California Institute of Technology, in consultation with one of us (A.P.I.). An independent set of similar calculations was performed at the University of Wisconsin–Madison, confirming our calculations.
- J. W. Warwick *et al.*, Voyager press conference at the Jet Propulsion Laboratory, Pasadena, CA, 27 August 1989; J. W. Warwick *et al.*, in preparation.
- B. A. Smith et al., Science 233, 43 (1986).
 B. A. Smith et al., ibid. 213, 163 (1981); B. A. Smith et al., ibid. 215, 504 (1982).
- 16. This research was supported by NASA, primarily through the Voyager Project Office at the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech). H.B.H. acknowledges the support of a National Research Council Resident Research Associateship, sponsored by JPL-Caltech, through an agreement with NASA. We thank D. Hinson for pointing out an error in the preliminary calculations. We also thank D. A. Alexander, L. Wynn, and G. W. Garneau for processing and preparation of the photos.

4 August 1989; accepted 17 August 1989

Negative Differential Resistance on the Atomic Scale: Implications for Atomic Scale Devices

IN-WHAN LYO AND PHAEDON AVOURIS

Negative differential resistance (NDR) is the essential property that allows fast switching in certain types of electronic devices. With scanning tunneling microscopy (STM) and scanning tunneling spectroscopy, it is shown that the current-voltage characteristics of a diode configuration consisting of an STM tip over specific sites of a boron-exposed silicon(111) surface exhibit NDR. These NDR-active sites are of atomic dimensions (~1 nanometer). NDR in this case is the result of tunneling through localized, atomic-like states. Thus, desirable device characteristics can be obtained even on the atomic scale.

HERE HAS BEEN A CONTINUING EFfort to decrease the dimensions and to understand the size limitations of microelectronic devices. At small dimensions, most conventional device structures face fundamental and technological limitations. At very small dimensions characteristic quantum effects become prominent, which, while placing limits on the size of conventional devices, can be exploited to create a new class of quantum effect devices such as quantum wells and their one- and zero-dimensional analogs, quantum wires and quantum dots (1). Another device that exploits quantum effects, electron tunneling in particular, is the Esaki diode (2). A common characteristic of both types of quantum effect devices, that is, Esaki diodes and quantum-well type structures, is the presence of regions of NDR in their curves

of current versus voltage (I-V). NDR, which is the phenomenon of decreasing current with increasing voltage, is the essential property that allows such devices to be used as fast switches, oscillators, and frequency-locking circuits (1, 3).

In this work, we demonstrate that NDR can occur in structures of atomic dimensions $(\sim 1 \text{ nm})$. These structures involve a tunnel diode configuration formed by specific surface sites and an STM tip. STM and scanning tunneling spectroscopy (4) are used to characterize these surface sites and measure their *I-V* characteristics. We also present a simple model to explain NDR at the atomic level.

We have observed NDR in several surface chemical systems. In all cases, NDR developed at localized surface sites. Here we will discuss examples involving structures produced by the adsorption of boron on silicon, Si(111). This system is particularly well suited for the observation of NDR because

IBM Research Division, T. J. Watson Research Center, Yorktown Heights, NY 10598.



Fig. 1. (a) STM topograph of the surface produced by exposing Si(111) to 1 Langmuir of decaborane and thoroughly annealing to 1000°C. Sample bias = 2 V. (b) Localized defect site exhibiting NDR.

of the occurrence of several specific surface sites formed upon B adsorption (5).

Our scanning tunneling microscope and the setup for obtaining *I-V* curves over specific atomic sites have been described in detail elsewhere (6). We deposited the B by exposing the Si(111) surface to decaborane (B₁₀H₁₄) at room temperature and by subsequently annealing the sample to temperatures above the hydrogen desorption temperature (>500°C). Under these conditions, the well-known 7×7 Si reconstruction is eliminated and a new ($\sqrt{3} \times \sqrt{3}$) R30°



Fig. 2. Schematic of the experimental arrangement and tunneling current versus sample bias (I-V) curves. Curve a: Normal I-V curve obtained over the majority sites of Fig. 1a. Curves b and c: I-V curves obtained over defect sites such as that shown in Fig. 1b. Curves b through d show regions of NDR. The current scale is 0.5 nA per division.

structure is formed. Such a structure has been observed by low-energy electron diffraction after B deposition on Si(111) from the gas phase (7) or by surface segregation induced by thermal annealing of heavily Bdoped samples (8). Similar $(\sqrt{3} \times \sqrt{3})$ R30° structures have been observed after the deposition of other group III elements such as aluminum (9) and indium (10) on Si(111). In those cases the group III atom occupies a threefold site over a second-layer Si atom. This configuration is usually referred to as a T_4 adatom configuration. However, B is different from these other group III atoms in that it has a smaller covalent radius than Si. Because of this, B in a T₄ adatom configuration introduces strong tensile strain. Our studies (5), based on the use of STM and parallel ion-scattering measurements and first-principles electronic structure calculations, indicate that the thermodynamically most stable configuration involves an unusual geometry, where B occupies a substitutional site directly below a Si adatom at a T_4 site. We denote this site as the B_s configuration. The configuration involving B as an adatom (B-T₄), although less stable than the B_s configuration by about 1 eV (5), requires less activation energy for its formation. In addition, the presence of B stabilizes a configuration involving Si adatoms at T_4 sites (Si- T_4). The actual surface structure is determined by both thermodynamic and kinetic considerations. Depending on the amount of B and the annealing temperature, a variety of surface sites including Si-T₄, B-T₄, and B_s sites can be present. For decaborane exposures >1Langmuir and after annealing to 1000°C, Bs is the dominant configuration and is responsible for the $(\sqrt{3} \times \sqrt{3})$ R30° structure shown in Fig. 1a. There are still, however, several minority sites.

The I-V curves of such minority sites can exhibit NDR. A schematic of the experimental arrangement and the I-V curves are shown in Fig. 2. Curve a is a normal I-Vcurve characteristic of the majority sites of the surface shown in Fig. 1a. Curves b through d show regions of NDR. During our STM studies and over different minority sites we have observed three different types of NDR behavior: NDR developed either for negative sample bias (curve b) or for positive sample bias (curve c) or for both biases (curve d).

The essential requirement appears to be the presence of localized states. Such states



Fig. 3. Computer simulations of I-V characteristics. The barrier height and the tip-to-surface distance are 4 eV and 8 Å, respectively. (Left) DOS for three localized states of sample and tip. (**Right**) Resulting I-V curves.

are produced naturally in the sample when a given minority site is surrounded by majority sites. In such a case the wave function can be confined by the surrounding solid and the vacuum barrier. In effect, an analog of a quantum dot is formed, which is smaller by at least two orders of magnitude than any quantum dot structure to date (1). However, unlike quantum dots, the discrete states formed are not the result of size quantization but are localized quasi-atomic states. An NDR site that shows a type b *I-V* curve (Fig. 2) is shown in Fig. 1b. NDR appears when the STM tip is over the bright inner core of this site. Thus, NDR is localized in a region of about 10 Å. On the basis of localdensity-functional theory calculations (5), we tentatively identify this site as involving a missing Si adatom over a B_s site. In this way, a localized state involving three Si dangling bonds is formed. In other experiments we find type c I-V behavior over Si-T₄ sites. Such NDR behavior has also been observed recently by another group (11). Type d *I-V* behavior is observed over more complex, as yet unassigned sites.

Although localized states at the sample appear to be essential for the development of NDR, we have evidence that the tip electronic structure is equally important. In fact, we have observed rest-atom NDR over adatom sites of the clean Si(111) (7×7) surface after the tungsten tip became coated with Si by crashing into the Si sample. Because of the large separation between rest-atoms on the 7×7 surface, the Si adatom surface states are localized, as is evidenced by the lack of dispersion in angularly resolved photoemission (12). When atomic resolution is achieved by STM, it is expected that tunneling at the tip involves very few (for example, one to three) tip atoms on top of a macroscopic tip surface. Under these conditions we do not expect that the relevant tip states are extended states; most likely they can be described as adsorption-induced resonances with a Lorentzian-like density of states (DOS) (13). The width of such states depends on the number of atoms that are involved in the tunneling and their coupling to the rest of the tip. For example, if tunneling occurs out of an impurity atom that is relatively weakly coupled to the tip, the relevant tip DOS can be quite narrow. During an STM experiment, the structure of the active area of the tip and even the chemical nature of the tip atom directly involved in the tunneling can change as atoms move on the surface of the tip.

Using the idea that NDR arises as a result of tunneling between localized states, we have performed simulations of I-V characteristics for the sets of DOS for sample and tip shown in Fig. 3 (left) and a simple one-

dimensional model for the tunneling barrier. The DOS of the sample states were obtained through STM measurements with "normal" tips, that is, tips with which no NDR behavior is observed and which give tunneling spectra for the majority sites that are in agreement with conventional spectroscopy (14). The results are shown in Fig. 3 (right). When the bias voltage is varied, the peaks in DOS shift with respect to each other. When the peak positions coincide, the tunneling current exhibits a maximum in cases a and b. In case c, maxima are observed when the Fermi level crosses a peak in the DOS. Similar behavior was observed in a firstprinciples calculation by Lang (15). From Fig. 3 it is clear that by including sites with prominent localized occupied or unoccupied states, we can account for all observed I-Vbehaviors shown in Fig. 1. These results provide support for our proposal that the mechanism of NDR involves tunneling between localized atomic-like states.

Our results show that the property of NDR can be realized in the I-V characteristics of a diode formed by an STM tip and localized surface sites. In the future it may be possible to construct atomic scale devices that use the characteristics of atomic wave functions.

REFERENCES AND NOTES

- 1. H. Heinrich, G. Bauer, F. Kucher, Eds., Physics and Technology of Submicron Structures (Springer Series in Solid State Sciences, vol. 83, Springer-Verlag, Berlin, 1988).
- 2. L. Esaki, Phys. Rev. 109, 603 (1958).
- 3. S. M. Sze, The Physics of Semiconductor Devices (Wiley-Interscience, New York, 1981).
- G. Binnig and H. Rohrer, *Rev. Mod. Phys.* 57, 615 (1987);
 C. F. Quate, *Phys. Today* 39, 26 (August 1986);
 R. M. Tromp, R. J. Hamers, J. E. Demuth, *Science* 234, 304 (1986);
 P. K. Hansma, V. B. W. Gokow, and A. Standard, A. Standard, A. Standard, A. Standard, C. Standard, S. Standard, C. Standard, S. Standard, S. Standard, S. Standard, C. Standard, S. Elings, O. Marti, C. E. Bracker, ibid. 242, 209 (1988)
- 5. I.-W. Lyo, E. Kaxiras, Ph. Avouris, Phy. Rev. Lett., in press.
- 6. Ph. Avouris and R. Wolkow, Phys. Rev. B 39, 5091 (1989); R. Wolkow and Ph. Avouris, Phys. Rev. Lett. 60, 1049 (1988).
- 7. H. Hirayama, T. Tatsumi, N. Aizaki, Surface Sci. 193, L47 (1988). V. V. Korobtsov, V. G. Lifshits, A. V. Zotov, *ibid*.
- 8. 195, 467 (1988)
- 9. R. J. Hamers and J. E. Demuth, Phys. Rev. Lett. 60, 2527 (1988).
- 10. J. Nogami, S. Park, C. F. Quate, Phys. Rev. B 35, 4137 (1987). 11. P. Bedrossian, D. M. Chen, K. Mortensen, J. A.
- Golovchenko, Bull. Am. Phys. Soc. 34, 720 (1989).
 R. I. G. Uhrberg, G. V. Hansson, J. M. Nicholls, P. E. S. Persson, Phys. Rev. B 31, 3805 (1985).
- 13. N. D. Lang and A. R. Williams, ibid. 18, 616
- (1978).14. E. Kaxiras, K. C. Pandey, F. J. Himpsel, R. M.
- Tromp, in preparation. 15. N. D. Lang, *Phys. Rev. B* **34**, 5747 (1986).
- 16. We acknowledge useful discussions with N. D. Lang

15 May 1989; accepted 2 August 1989

Spontaneous Vesicle Formation in Aqueous Mixtures of Single-Tailed Surfactants

ERIC W. KALER, *+ A. KAMALAKARA MURTHY, * BEATRIZ E. RODRIGUEZ,* JOSEPH A. N. ZASADZINSKI

Spontaneous, single-walled, equilibrium vesicles can be prepared from aqueous mixtures of simple, commercially available, single-tailed cationic and anionic surfactants. Vesicle size, surface charge, or permeability can be readily adjusted by varying the ratio of anionic to cationic surfactant. Vesicle formation apparently results from the production of anion-cation surfactant pairs that then act as double-tailed zwitterionic surfactants. These vesicles are quite stable in comparison to conventional vesicles prepared by mechanical disruption of insoluble liquid crystalline dispersions.

ESICLES, WHICH ARE SINGLE-BIlayer shells 30 to 150 nm in diameter, are widely used as model membranes, capsules for agents in assays and drug delivery, microreactors for artificial photosynthesis (among other reactions), and substrates for a variety of enzymes and proteins (1, 2). Although vesicles often form spontaneously in vivo, they have only rarely been observed to form in vitro without the input of considerable mechanical energy (such as sonication or pressure filtration) or elaborate chemical treatments (detergent dialysis or reverse-phase evaporation) (1-3). Vesicles formed in this way are metastable and eventually revert to multilamellar liquidcrystalline aggregates. This reversion is invariably accompanied by a release of the vesicle contents and the failure of the vesicle carriers. The lack of a simple and general method for producing spontaneous and stable vesicles has inhibited further progress in

E. W. Kaler, A. K. Murthy, B. E. Rodriguez, Depart-ment of Chemical Engineering, BF-10, University of Washington, Seattle, WA 98195.

J. A. N. Zasadzinski, Department of Chemical and Nuclear Engineering, University of California, Santa Barbara, CA 93106.

^{*}Present address: Department of Chemical Engineering, University of Delaware, Newark, DE 19716. †To whom correspondence should be addressed.