

located less than 1.6 kpc from Earth, and the transition from LMXB to millisecond pulsar happened within the past 10 years. Both of these facts suggest that many more, similar systems remain to be identified. Furthermore, having archival observations about the state of the system in its x-ray-emitting phase and the distinct possibility that the system may revert to an active LMXB allow one to learn more about conditions that have to be met to enable the onset of radio emission.

It is intriguing that the system parameters studied by Archibald *et al.* appear as textbook values: The orbit has a very small eccentricity, indicating that during the accretion period the expected tidal interactions circularized the orbit and aligned all spin vectors in the system. The mass of the companion lies between 0.14 and $0.42M_{\odot}$, a range that is typical for millisecond pulsar companions. The observa-

tions suggest that the companion is also being irradiated by the emission and wind from the pulsar, as for several other radio millisecond pulsars. Every little detail of the system seems so far to confirm the scenario that was boldly put forward by theoreticians 35 years ago.

However, there remain some blanks to fill in. We still do not know how fast a millisecond pulsar can be spun-up by an accretion process, i.e., what is the smallest spin period of neutron stars? The present record for the smallest spin period is 1.39 ms (12), but how far can we go? There will be a limit given by the properties of superdense matter, but other processes such as gravitational radiation losses may also limit accretion torques and hence the maximum spin frequency (13). The hunt for submillisecond pulsars is certainly on, both in electromagnetic as well as gravitational wave windows to the universe.

At least now we can be sure that our basic model is correct.

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APPLIED PHYSICS

Novel Probes for Molecular Electronics

Ernst Meyer and Thilo Glatzel

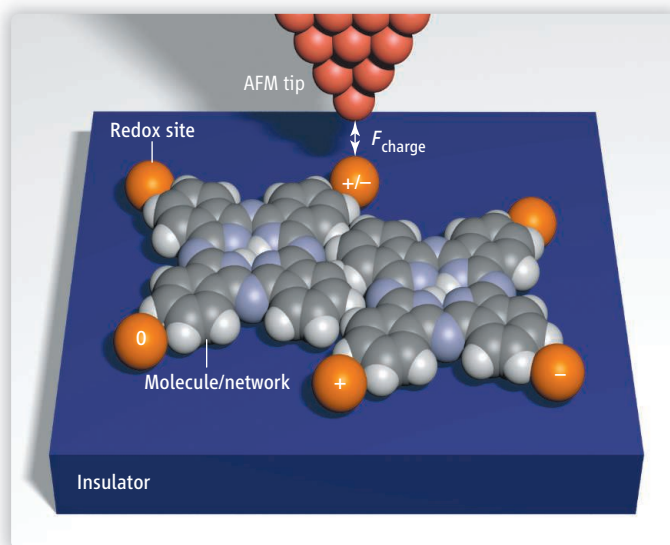
In molecular electronics, interactions between the molecules and the underlying substrate must be minimized to ensure that their electronic properties are not disturbed. Insulating films or bulk insulators are ideal substrates in this regard. However, insulating substrates require characterization tools that do not depend on conductivity. One possibility is to probe molecules on ultrathin insulating films with low-current scanning tunneling microscopy (STM) (1). Alternatively, non-contact atomic force microscopy (AFM) (2) can be used to image molecules on insulating films or bulk insulators. On page 1428 of this issue, Gross *et al.* (3) use an extension of the latter technique to image adatoms on thin insulating films and to probe the charge state of these adatoms. This powerful tool may find applications well beyond molecular electronics.

Orbital imaging of molecules on thin insulating films by STM was an important milestone, where

the influence of the substrate on the molecular wave functions was found to be negligible, in contrast to the situation on metallic substrates (4). Recently, immobilized molecules were imaged on bulk insulators at room temperature by noncontact AFM with submolecular resolution (5). However, the electronic properties of single molecules or atoms, such as the charge state, were not yet accessible.

An extension of noncontact atomic force microscopy allows detection and manipulation of the charge states of individual atoms.

Gross *et al.* now show that noncontact AFM not only allows single atoms or molecules to be imaged, but can also be used to detect the charge state of adatoms on thin insulating films. For this purpose, the authors have implemented an extension of non-contact AFM—called Kelvin probe force microscopy—at low temperatures. In Kelvin probe force microscopy, the electrostatic force is measured separately as a function of voltage (6, 7). Under appropriate measurement conditions, this method allows the local work function of the substrate to be determined with nanometer resolu-



Measuring charge transport in single molecules. Gross *et al.* show that a single molecule or molecular network on an insulator can be probed by attaching metallic adatoms, allowing single electron charges to be injected with a noncontact AFM tip. Subsequently, the charge transport can be investigated by measuring the charge states of all terminal adatoms with Kelvin probe force microscopy. F_{charge} is the force between the charge and the AFM tip.

Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland. E-mail: ernst.meyer@unibas.ch

tion. Gross *et al.* show that the method is sufficiently sensitive to distinguish the charge states of individual adatoms decoupled from the substrate by an ultrathin insulating ionic layer. Therefore, the authors can distinguish a neutral from a positively or negatively charged atom.

This achievement has tremendous consequences for the field of molecular electronics. It remains extremely difficult to electrically connect single molecules and to measure their electrical conductance. Most current lithography methods (8) yield metallic wires some tens of nanometers in diameter, much larger than the diameter of the molecules (typically on the order of 1 nm). This problem can be overcome by using geometries such as break junction experiments (9) and lifting up molecular or metallic wires by an STM tip (10). However, these methods do not allow spatial and electrical information to be obtained simultaneously without destroying the molecular structure. The crucial advance of Gross *et al.* is to perform their experiments without wiring the object of interest. This approach allows individual charges to be added to or removed from an atom and furthermore enables the direct measurement of the charge state.

The method of Gross *et al.* can be extended to molecules or molecular networks,

where charges can be added or removed at specific sites of the molecules (redox sites). Subsequently, the whole molecule or molecular network can be characterized by Kelvin probe force microscopy or optical techniques to investigate the charge transport or conformation changes. In a recent study, Glatzel *et al.* demonstrated the contacting of single molecular structures assembled on insulating surfaces by metal clusters as well as their distinction by local Kelvin probe force microscopy measurements (11). By combining this approach with single atoms connected directly to the molecular structure, the charge transport can in principle be investigated without applying an external electrical current. The AFM tip can alter the charge state of one of the metallic terminals (see the figure). Afterward, the change of the charge states of the other terminals can be measured by Kelvin probe force microscopy, elucidating the propagation of charges in the molecule or molecular network. Comparison with theoretical models will give the opportunity to learn more about the energy landscape of the molecules, which is probed by single injected electrons.

A change of atomic or molecular charge state is a central feature in many chemical reactions. Combining the redox sites—that is, the metal atoms or clusters connected to

the molecular structures—with probe microscopy therefore provides a novel tool for manipulating individual molecules and for performing chemical, electrochemical, or photochemical reactions with a high degree of control. In combination with optical excitation (12), it will allow absorption and charge generation to be measured at the molecular scale. This method is thus not only of interest for molecular electronics, but also for catalysis, material synthesis, and photovoltaics.

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MATERIALS SCIENCE

Silicon Carbide as a Platform for Power Electronics

C. R. Eddy Jr. and D. K. Gaskill

For high-voltage, high-current devices that can be operated at elevated temperatures, silicon carbide (SiC) has been the material of choice. Efforts to produce single-crystal SiC began 30 years ago, but intrinsic problems in growing high-quality single-crystal boules free of micropipe defects—micrometer-scale pinholes created by dislocations—have only recently been overcome. A series of developments in crystal growth have made large-area, high-quality SiC substrates readily available for applications such as high-frequency transmitters and solid-state white lighting. Additional reductions in defects in the

active region of devices have been achieved through epitaxial approaches, in which single-crystal layers are grown on the substrate. SiC is now poised as the linchpin to “green energy” that will replace less energy-efficient switches now based on silicon technology.

The choice of a semiconductor for switching electrical currents on and off depends on the operating voltage and how much current must be controlled. Silicon is an excellent material for the low-power transistors used in microelectronics, but for high currents and voltages, its implementation becomes complex and thermal management issues arise. The fundamental properties of SiC make it a better choice under these conditions.

One reason why SiC has been of fundamental interest to materials scientists is that it

exists in more than 200 stacking modifications (polytypes) (1). With the advent of the vapor-phase Lely growth process in 1955, small, high-quality SiC single-crystal platelets (about 1 cm² in area) could be made (2). The most readily synthesized hexagonal polytypes, 4H and 6H, have a large indirect band gap (~3.2 eV) and a large breakdown electric field (2 MV cm⁻¹), as well as high electron mobility (900 cm² V⁻¹ s⁻¹) and thermal conductivity (400 W m⁻¹ K⁻¹). Given these properties, SiC power switches should have performance figures of merit 10 to 100 times those of silicon switches.

The growth of SiC crystals presents many challenges. A SiC boule is typically grown by transporting its physical vapor to a seed crystal chosen to be as defect-free as possible. This

Methods for growing large, defect-free silicon carbide crystals have enabled the fabrication of devices that can operate at high power.

U.S. Naval Research Laboratory, 4555 Overlook Avenue SW, Washington, DC 20375, USA. E-mail: david.gaskill@nrl.navy.mil; charles.eddy@nrl.navy.mil