Observation of Landau levels at the InAs(110) surface by scanning tunneling spectroscopy

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Low-temperature scanning tunneling spectroscopy measurements on clean InAs(110) surfaces demonstrate the possibility to investigate Landau quantization with subnanometer resolution. Separate Landau levels are resolved at magnetic fields of 2 T and larger. Experiments with different tips show a significant tip dependence. In zero field resonances are observed near the onset of the conduction band, which are attributed to tip-induced band bending. Although Landau quantization is only present parallel to the sample surface, the Landau levels give a large contribution to the total tunnel current. [S0163-1829/97/52424-6]

Recently, several experiments1–5 have demonstrated the possibility to use scanning tunneling microscopy to investigate the spatial behavior of the conduction and valence bands in the vicinity of distortions in the electrostatic potential. The edges of these bands determine the transport properties of a semiconductor, and therefore the possibility to investigate the energy bands spatially resolved can be of great value. In semiconductors, the Fermi wavelength and also the screening length exceed the atomic scale. As a consequence dopants just below the surface can influence the carrier density at the surface. Johnson et al.1 and Zheng et al.2 have shown that these local variations in the band bending appear as hill- or locklike features in scanning tunnel microscope (STM) images of the GaAs(110) surface, superimposed on the atomic sublattice (see also Ref. 3). On III-V semiconductor heterostructures Feenstra et al.3 were able to resolve the subband energies of a superlattice and to characterize the roughness of the interfaces5 by scanning tunneling spectroscopy. In their experiments the measurements were performed at room temperature on clean cross-sections of the heterostructure after it was cleaved under UHV conditions.

In this paper we demonstrate that scanning tunneling microscopy also allows the direct, spatially resolved observation of the quantization of conduction electrons into Landau levels in an external magnetic field. Since the energy scales of Landau-level quantization are much smaller than those related to dopants and heterostructures, the STM in our experiments is operated at 4 K, which yields a significant increase in the spectral resolution ($k_B T \sim 0.4$ meV at 4 K) compared to room temperature. The enhanced resolution also enables us to examine the onset of the conduction band in the $I$-$V$ curves in zero field in more detail. In our measurements on clean InAs(110) surfaces we observe sharp resonances that are strongly tip dependent.

The opportunity to investigate Landau levels with the lateral resolution of an STM opens interesting experimental prospects. Transport properties in two-dimensional electron gases subjected to Landau quantization are highly anomalous. The most famous example is the quantum Hall effect, discovered by von Klitzing, Dorda, and Pepper in 1980.6 During the last decade it has become clear that the spatial evolution of the Landau levels near the edges of a two-dimensional electron gas (2DEG) leads to the formation of so-called edge states,7 which are responsible for many of the transport phenomena. Recently these edge states have been imaged to a lateral resolution of a few micrometers, using optical means.8 Imaging the Landau levels with nanometer resolution could yield detailed information about sizes and shapes of the edge channels and allow comparison to self-consistent theories.9

For our experiments we have chosen InAs because of its small effective electron mass at the conduction band edge, $m_{eff} = 0.023 m_e$, resulting in a significant Landau-level splitting already at low magnetic fields. Also, in the presence of Fermi-level pinning, surfaces of InAs can contain surface 2DEG’s.10–12 InAs is a small band-gap semiconductor, $E_g = 350$ mV, and as most III-V semiconductors, has a zinc-blende structure.

The electronic properties of InAs surfaces have been studied by various other techniques. The existence of a surface 2DEG, due to surface pinning of the Fermi level in the conduction band, was for the first time indicated in transport measurements by Kawaji and Gatos.10 Tsui investigated the $n$-type InAs accumulation layer by planar tunneling spectroscopy and was able to directly determine the energies of the Landau levels, both in the surface 2DEG and in the bulk conduction band.11,12 The planar method used by Tsui is based on the same principles as tunneling spectroscopy with an STM. In the planar geometry usually an oxide is used as an insulator between the two electrodes, whereas in an STM geometry the vacuum barrier separates the electrodes. The use of the vacuum barrier and the lateral scanning capability, however, allows us to discriminate between contributions
from contaminants and defects versus those of the actual surface and also opens the possibility to obtain spatially resolved information.

The experimental objective here has been to observe Landau levels at the semiconductor surface with an STM. For this we have preferred to investigate clean surfaces without deliberate Fermi-level pinning. In order to establish these surfaces we have performed our experiments with a low-temperature STM equipped with an *in situ* cryostat. The STM is mounted in a cryostat, inside the bore of a superconducting 10 T magnet. At liquid He temperatures the vapor pressure of oxygen is extremely low (<10⁻¹⁵ Torr). Surfaces of III-V compound semiconductors, which normally oxidize very quickly, will stay free of contaminants for many days under these conditions. The InAs used in our experiments is lightly doped, n = 2.5 × 10¹⁶ cm⁻³, yielding a Fermi energy of 10 meV. This doping concentration ensures a finite bulk conductivity at low temperatures, irrespective of the presence of a surface 2DEG. All the measurements presented here are performed with Pt(90%)Ir(10%) tips, cut in ambient with scissors. The bias voltages are applied to the sample relative to the tip. This implies that at positive voltages the Fermi level of the tip is lined up in the conduction band of the InAs. A schematic energy diagram is shown in Fig. 1.

On surfaces that were cleaved *in situ* at low temperatures, atomic resolution was easily achieved. Depending on the polarity of the bias voltage either the In or the As atoms are imaged. The images are similar to those obtained by Feenstra et al. on GaAs (Ref. 14) and depend on the polarity of the bias voltage. Spectroscopy curves on the clean InAs(110) surfaces give a band gap of 0.50 ± 0.10 V, larger than the expected value of 0.35 V. The deviation is attributed to tip induced band bending. We omit the discussion of the large-scale spectroscopic features here (see Ref. 15) and focus on some of the details that are revealed because of the enhanced spectroscopic resolution.

In the majority of our experiments we observed sharp features in the *dI/dV* near the onset of the conduction band [Figs. 2(a) and 2(b)]. These features are not due to defects or contaminants at the surface, since by topography it is assured that spectra are taken on flat and clean terraces, tens of nanometers away from any irregularity present at the surface. The occurrence and the energies of these sharp resonantlike features is tip dependent. With a particular tip, *I*-*V* curves are identical over the whole surface (with the exception of areas with steps and defects).

Figure 2(c) shows *dI/dV* curves obtained with magnetic fields of 3 T and 4 T applied perpendicular to the surface. Besides the peaks below the conduction band edge, which were already present at zero field, oscillations in the *dI/dV* at higher voltages are present. The period of the oscillations scales with the applied magnetic field. From Fig. 2(c) we determine the periods to be ∼12 mV at 3 T and ∼16 mV at 4 T. These values are of the same order as the expected Landau-level splittings (*h*B/*m*ₜₜ*), of 15 mV and 20 mV (with *m*ₜₜ=0.023mₑ). We therefore conclude that the oscillations in the *dI/dV* are due to Landau quantization in the plane of the sample surface. An important question that has to be addressed is whether the oscillations originate from bulk electrons or from a possible surface 2DEG.

In Fig. 3(a) the voltages at which the oscillation maxima occur are shown as a function of the Landau-level number *l* for different magnetic fields. From this figure we can clearly distinguish two regimes: one where the Landau-level separation is nearly constant, and another where the separation is not constant and where the voltages corresponding with the maxima of the oscillations are tip dependent.

In the bulk conduction band the Landau-level separation is constant and scales with magnetic field. From the oscilla-

![FIG. 2. (a) *I*-*V* spectra near the onset of the conduction band. The resonances in the *dI/dV* (b) are reproducible and independent of position (also the small ones indicated by the arrows). In some cases no resonances are observed. The curves are offset for clarity. (c) *dI/dV* at *B* = 3 T and *B* = 4 T. Oscillations at positive sample voltages scale with magnetic field. The *B* = 3 T curve is shifted by 4 nA/V for clarity.]
OBSERVATION OF LANDAU LEVELS AT THE...
and the sample surface is likely to influence both experiments. Although He is an inert gas its presence at the tip function of the tip. For heat exchange purposes a small exposure to air cannot be avoided, leading to a lower work practically however, contamination of the tip surface due to extraction that the tip is composed of material inside the wire. Realistically, however, contamination of the tip surface due to exposure to air cannot be avoided, leading to a lower work function of the tip. For heat exchange purposes a small amount of He is present in the vacuum can during the experiments. Although He is an inert gas its presence at the tip and the sample surface is likely to influence both work functions.

In conclusion, we have performed tunneling spectroscopy measurements with an STM on clean InAs(110) surfaces at low temperatures. Landau levels have been observed by scanning tunneling spectroscopy. The strongly enhanced energy resolution at low temperature allows the investigation of $I-V$'s on semiconductor surfaces in significantly more detail than at room temperature. This enables to resolve separate Landau levels already at relatively low magnetic fields. Our data show that every tip uniquely influences the spectra near the onset of the conduction band. At zero field sharp resonances are observed that are attributed to the formation of a “dot” via tip-induced accumulation at the InAs(110) surface.

The absence of surface states near the band gap results in measurements that are strongly tip dependent. To reduce the influence of the electric field of the tip the Fermi level has to be pinned at the semiconductor surface. Fermi-level pinning can be realized for example by depositing a thin layer of adsorbates on the surface or by cleaving the semiconductor in such a way that a large density of steps is obtained at the surface. To establish a surface two-dimensional electron gas the Fermi level at the surface has to be pinned in the conduction band.

The Landau-level measurements show that a significant fraction of the tunnel current is carried by states parallel to the sample surface. Landau levels at semiconductor surfaces may provide a convenient system to investigate conservation in the STM tunnel geometry.

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16. The labeling of the peaks by the Landau-level numbers $l$ is somewhat arbitrary. We extended the solid line fits to low voltages and assigned the Landau-level numbers in such a way that the 0th Landau level would be just above $V_{\text{sample}} = -10 \text{ mV}$ (the bottom of the conduction band). The measured Landau-level positions are influenced by tip-induced band bending.
23. The presence of helium has been found to influence the tunnel current between two metal electrodes: R.J.P. Keijser et al., Phys. Rev. Lett. 76, 1138 (1996).