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Discovery of New Quantum Properties for Electrons Near the Surface of a Semiconductor

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Electrons near the surface of semiconducting indium nitride have been discovered to exist in "quantum well" states, which are remarkably simple fundamental energy states. It is highly unusual to observe such states in ordinary materials; usually they are observed only in engineered materials or electronic devices. We discovered the quantum well states by irradiation of indium nitride with intense x-rays, which caused the electrons in these states to be ejected from the material into vacuum, where their energy and momentum was measured. This technique, known as photoemission spectroscopy, allowed us to make the first definitive determination of these properties.

We have directly observed a quantized electron accumulation layer near the surface of the narrow gap semiconductor indium nitride (InN) using high-resolution Angle Resolved Photoemission Spectroscopy (ARPES). Electron accumulation is a phenomenon observed in certain semiconductors whereby a higher density of electrons is observed in a layer near the surface of the solid. It is postulated that the surface region in InN has a higher charge density than the bulk due to N vacancies or donor-type surface states. This causes the surface Fermi level to lie in the conduction band. We have discovered that not only are electrons observed far above the conduction band minimum, but these electrons are found to be quantized perpendicular to the surface, i.e. the electrons in the accumulation layer have been determined to reside in quantum well states.

Authors (from left to right) Yufeng Zhang, Leyla Colakerol, Shancai Wang, Lukasz Plucinski, Tim Learmonth, Sarah Bernardis, and Kevin Smith.

Figure 1 presents an ARPES photocurrent intensity map of emission from the states within 1.5 eV of E_F, recorded with an incident photon energy of 69 eV, from a sample annealed in UHV to 300 EC for 30 minutes. The sample was held at 177 K during measurement. The horizontal axis is the angle of emission, converted to momentum at each point, while the vertical axis is the binding energy; the intensity reflects the photocurrent for any particular binding energy and momentum. The momentum direction is along $\Gamma\Sigma M$, in the surface plane. Two well-resolved, nested bands are clearly observed, and these correspond to the quantum well states. ARPES was also used to measure the Fermi surface of the quantum well states, as well as their constant binding energy contours below the Fermi level, E_F. As is clear in **Figure 2**, the Fermi surface was found to consist of concentric, perfectly circular structures associated with each of two quantum well states, but the corresponding energy contours assume a hexagonal symmetry away from E_F. The Fermi level, and the size of the Fermi surface for these quantum well states could be controlled by varying the method of surface preparation. This is the first unambiguous observation that electrons in the InN accumulation layer are quantized, and the first time the Fermi surface associated with such states has been measured. The thin film samples were grown using molecular beam epitaxy at Boston University, with the experiments undertaken on beamline U5UA at the National Synchrotron Light Source and on beamline 12.0.1 at the Advanced Light Source, Lawrence Berkeley National Laboratory.

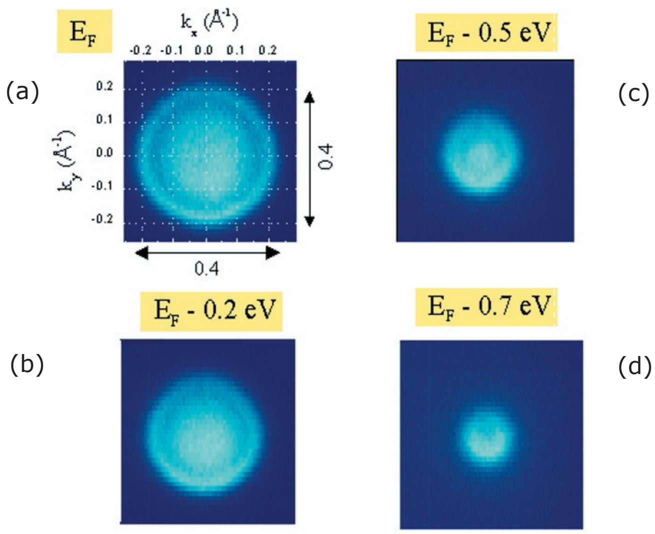

__Figure 1__. ARPES photocurrent intensity map of states within 1.5 eV of E_F. hν = 69 eV, and the sample temperature was 177 K. The sample was annealed to 300 °C in UHV for 30 minutes. The false color intensity reflects the photocurrent, with lighter intensity indicating higher current. The momentum direction is along ΓΣM, in the surface plane.

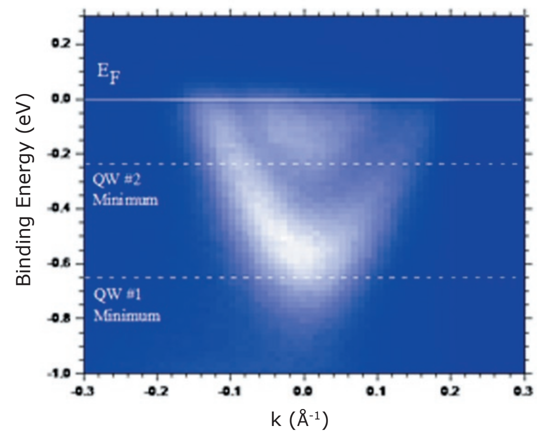

__Figure 2__. Fermi surface and constant binding energy contours. The photocurrent is plotted as k_x and k_y are varied, while the binding energy relative to E_F is kept constant at 0 eV (Fermi surface), 0.2 eV, 0.5 eV and 0.7 eV. hν = 70 eV, and sample temperature was 60 K. The diameter of the outer Fermi surface is 0.4 Å^{-1}.