FRG: Quantum Engineering of Metallic and Magnetic Nanostructures (DMR – 0306239)

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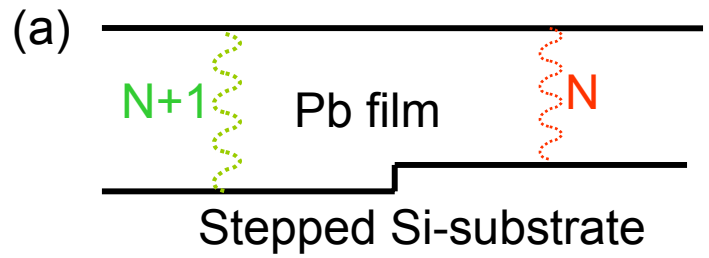
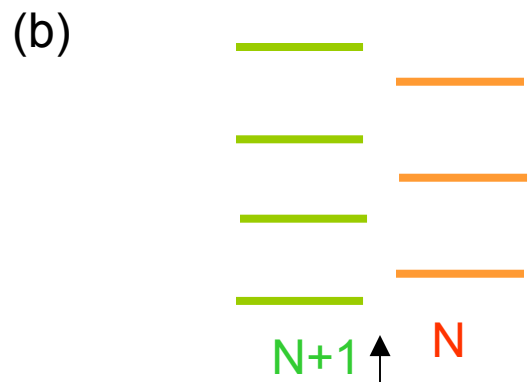
Visualization of inter-edge states between quantum wells

- Inter-edge states: 2D analogy of interface states at solid-solid interfaces.
- Mismatched quantum well states at the boundary → inter-edge states
- Using STM to map out "energy resolved" spatial distribution of inter-edge states
- Better understanding of generic interface states which impact almost all electronic devices
- Important implications for quantum-well based electronic devices



Different thickness → different quantum well states



Mismatched QWS at the boundary → inter-edge states

At the boundary of two dissimilar electronic systems, there often exist localized energy states. For solid surfaces, they are called surface states and at solid-solid interfaces called the interface states. In a reduced dimension system such as a 2D electron gas, edge states exist at the boundary between the bulk and the vacuum. Over many years, these topics have been at the focal points of scientific research owing to not only fundamental but technological interests. In particular, there have been tremendous driving force behind the investigation of "interface states" since their existence impacts the operation of almost *all electronic devices*. Yet, probing them is notoriously difficult due to the obstacle to access the solid-solid interface. Consequently, we know very little about their energy locations nor much about the spatial distribution. Here we report the direct observation of "inter-edge states" between two mismatched quantum well systems using a scanning tunneling microscope where we mapped out their energy locations and spatial distributions. The name "inter-edge states" is coined as a 2D analogy of the "interface states" for 3D solid-solid interfaces.

We prepared the sample by depositing a thin Pb film (deposition thickness of 1nm) on a stepped Si(111) 7x7 substrate (see schematic) at room temperature, resulting in isolated flat-top Pb mesas with an average lateral dimension of 300 nm and an average height of 2 nm (e.g. see our recent paper in PRL 92, 106104 (2004)). In spite of a 10% lattice mismatch, Pb films are grown epitaxially (i.e. (111) oriented) with strain fully relaxed. The flat-top geometry is caused by surface tension. The existence of the stepped substrate leads to regions of different local thickness (marked as N and N+1 in (a)). The vertical confinement of electron motion results in the existence of quantum well states (QWS). Different local thickness results in different QWS (see (b)). At the boundary, the energy locations of the two quantum well systems are mismatched, leading to the existence of inter-edge states. These inter-edge states first facilitate as a model system to provide a better understanding of their 3D counter part, the interface states. Moreover, as quantum well-based advanced electronic devices becomes smaller, small fluctuations in quantum well thickness will certainly result in mismatched QWS where inter-edge states are likely to have profound effects on device performances.

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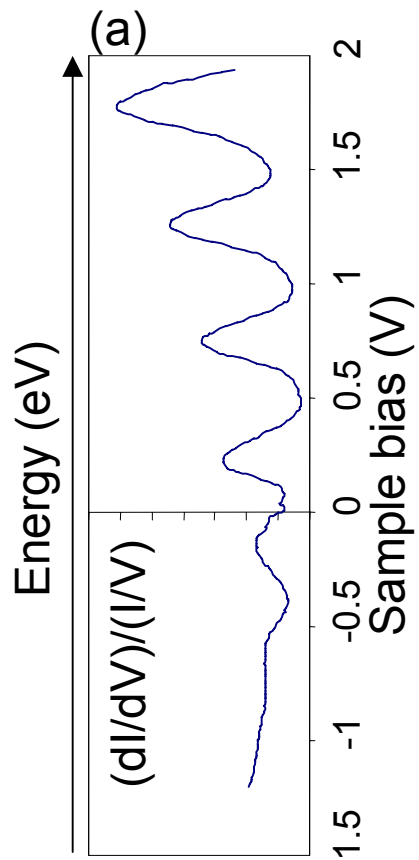
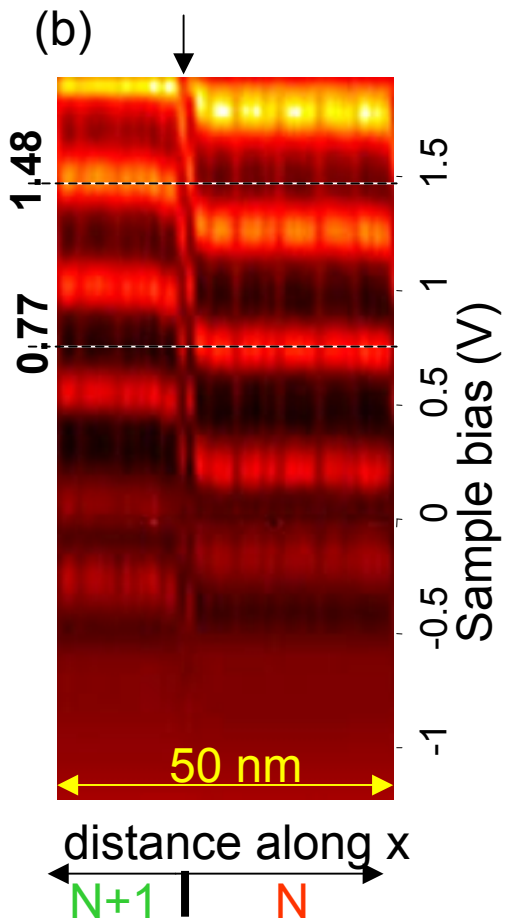
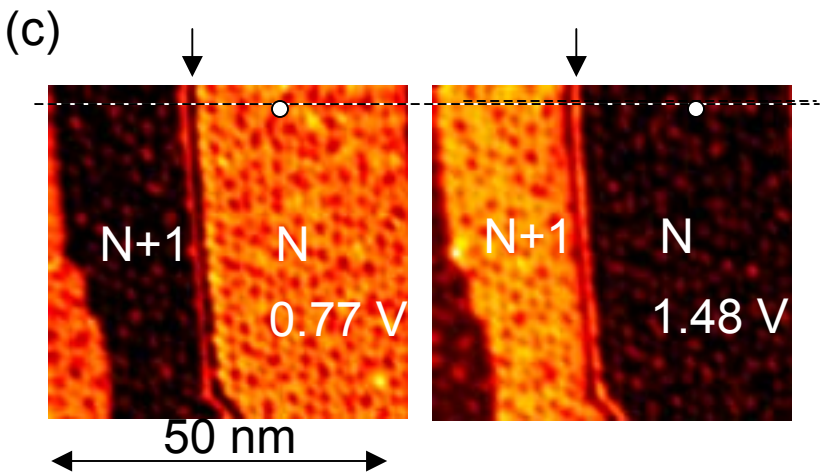
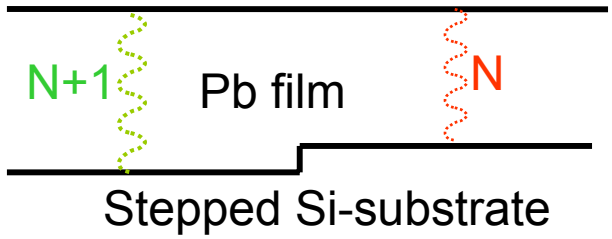


Tunneling spectrum of QWS measured at one location





Spatial mapping of inter-edge states at two different energies



Different thickness → different quantum well states

A low temperature STM (operated at 8 K) was used to probe the structural and electronic properties. Shown in (a) is the tunneling spectrum acquired at a point in region N (marked as a white dot in (c)) where the existence of individual QWS appears as individual peaks. Shown in (b) is the spatial dependence of the tunneling spectra along the x-direction (marked as the dashed line in (c). The difference in the quantization levels between the two regions are clearly visible. At the boundary where the energy levels are mismatched, inter-edge states exist (marked by the vertical arrow). For example, at 0.77 eV above the Fermi level (marked by the lower dashed line), the electron moving laterally from the QWS in region N toward region N+1 encounters an energy gap, resulting in "inter-edge states" which are clearly observable. Similarly, at 1.48 eV above the Fermi level (upper dashed line), the converse occurs. The 2D spatial mappings of the inter-edge states at these two energy locations are shown in (c) and marked by the arrows. It is interesting to observe that the spatial distribution of the inter-edge states shows a phase reversal at these two energy locations.

These inter-edge states first facilitate as a model system to provide a better understanding of their 3D counter part, the interface states. Moreover, as quantum well-based advanced electronic devices becomes smaller, small fluctuations in quantum well thickness will certainly result in mismatched QWS where inter-edge states are likely to have profound effects on device performances.

This research program started from our discovery of "quantum growth phenomena" where the quantum confinement of electrons in thin film plays an important role in determining the film stability. The program has now expanded to include investigation of important physical properties, including electronic, spintronic, magnetic and superconducting properties, of such "quantum engineered metallic nanostructures" on semiconductor substrates.

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Education:

One undergraduate student (J. Robertson), three graduate students (D. Eom, S. Qin, D. Culcer), and one postdoc (J. Li) are currently working on this project program.

Outreach:

Shih has organized two campus wide forums at the University of Texas, targeting Undergraduate Nano Education and Educational Outreach to the K-12 program. In addition, Shih and Niu have organized special seminar series for Nanoscience in the Physics Department of UT. They have also participated in the “pizza seminar” series and given tutorial lectures to new graduate students about FRG sponsored research.