Insights from scanning tunneling microscopy experiments into correlated electron systems

Benschop, T.

Summary

This thesis presents insights from our study of various correlated electron systems with a scanning tunneling microscope (STM). Correlated electron states occur is certain materials where the electrons strongly interact with each other. In ordinary metals, these electron-electron interactions also exist, but get substantially screened due to the sheer number of electrons. We therefore describe electrons in ordinary metals as a gaseous state of free, or weakly interacting charged particles. This adequately explains their properties, however, this picture does not work for correlated electron materials. The prominent electron-electron interactions present in these materials enable a wide range of exotic electronic phenomena, some of which are presented in this work.

In chapter 2, we present our STM results measured on an overdoped copper oxide (cuprate) compound.
The cuprate high-temperature superconductors exhibit many unexplained electronic phases, but it was often thought that the superconductivity at sufficiently high doping is governed by conventional mean-field Bardeen-Cooper-Schrieffer (BCS) theory. In contradiction to BCS theory, however, it turns our that the superfluid density (the number of paired electrons) vanishes when the critical temperature goes to zero. Our scanning tunneling spectroscopy measurements in the overdoped regime of the $(Pb,Bi)_2Sr_2CuO_{6+\delta}$ high-temperature superconductor show that the vanishing superfluid density can be explained by the emergence of puddled superconductivity, featuring nanoscale superconducting islands in a metallic matrix. Our measurements further reveal that this puddling is driven by gap filling, while the gap itself persists beyond the breakdown of superconductivity. The important implication is that it is not a diminishing pairing interaction that causes the breakdown of superconductivity. Unexpectedly, the measured gap-to-filling correlation also reveals that pair-breaking by disorder does not play a dominant role. We are therefore left to conclude that the mechanism of superconductivity in overdoped cuprate superconductors is qualitatively different from conventional mean-field theory.

In chapter 3, we study twisted bilayer graphene devices, and quantify their local twist angle and strain on the nanoscale.
The electronic properties of a twisted bilayer of graphene are heavily dependent on the exact twist angle. Because of the twist angle between the two graphene lattices, a moiré pattern appears. For most twist angles, the electronic properties of the bilayer

are trivial. However, at certain "magic" angles, the observed electronic properties of a graphene bilayer can no longer be explained by conventional band theory as a result of correlated electron physics. These magic angles are very fragile. Only in a small interval of a few tenths of a degree around the magic angle does this behavior occur. It is therefore of great importance to accurately measure the exact twist angle of a graphene bilayer. This can be done by imaging the emerging moiré pattern as the periodicity of this pattern directly depends on the twist angle. We introduce a new method to continuously map inhomogeneities of a moiré lattice and apply it to large-area topographic images we measure on open-device twisted bilayer graphene (TBG). We show that the variation in the twist angle of a TBG device is about 0.08° around the average of 2.02° over areas of several hundred nm, comparable to devices encapsulated between hBN slabs. This is important because throughout literature, devices with a supposed similar twist angle twist angle sometimes show different electronic behavior. Twist angle inhomogeneity is frequently conjectured to be the cause of these differences. Our method distinguishes between an effective twist angle and local anisotropy and relate the latter to heterostrain. Our results imply that for our devices, twist angle heterogeneity has a roughly equal effect to the electronic structure as local strain. The method introduced here is applicable to results from different imaging techniques, and on different moiré materials.

In chapter 4, we describe how to build and characterize the hardware needed to do noise spectroscopy measurements in a conventional, low temperature scanning tunneling microscope setup.
In conventional STM measurements, we only consider the time averaged, DC tunneling current. What is often neglected is the time dependent fluctuations in this tunneling current, which can give valuable insights in for example the nature of charge carriers in the material. We mostly disregard time dependent fluctuations as the severe limitation of bandwidth in conventional STM equipment make it impossible to measure them accurately. Here, we develop, build, and test a novel amplifier circuit capable of measuring the tunneling current in the MHz regime while simultaneously performing conventional STM measurements. This is achieved with an amplifier circuit including a LC tank and a home-built, low-noise high electron mobility transistor. The amplifier circuit is compatible with all conventional STM measurements, i.e., allowing for operation at junction resistances in the range of giga-ohms, and down towards point contact spectroscopy, enabling measurement with atomic resolution. To enable high signal-to-noise ratios and meet all technical requirements for the inclusion in a commercial low temperature, ultra-high vacuum STM, we use superconducting cross-wound inductors and choose materials and circuit elements with low heat load. We demonstrate the high performance of the amplifier by measuring the Poissonian shot noise of tunneling electrons on an atomically clean Au(111) surface.

In chapter 5, we present our noise spectroscopy measurements on Sr_2IrO_4, and explain how random telegraph noise could lead to the observed noise enhancements.
Sr_2IrO_4 is a Mott insulator exhibiting strong spin-orbit coupling. We present noise

spectroscopy measurements of the tunneling current between our STM tip and a Sr_2IrO_4 crystal. These results show substantial noise enhancements with respect to the normal Poissonian value, and appear to be highly localized. However, they do not appear to correlate strongly with any feature in the local density of states. The existence of substantial random telegraph noise (RTN) in addition to normal (Poissonian) shot noise can explain the noise spectra we observe. Fitting our data with a model results in characteristic frequencies of $\sim$ 100 GHz. We believe these noise enhancements indicate polaron formation in Sr_2IrO_4.