High Mobility Electrons in $SrTiO_3$ Heterostructures

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Perovskite oxides exhibit a broad range of physical properties – insulator, semiconductor, metal, superconductor, heavy fermion, ferromagnet, antiferromagnet, spin glass, charge/spin density wave transitions, ferroelectricity, piezoelectricity, etc. Many of these phenomena occur in materials that are lattice-matched within a few percent of one another, giving rise to the possibility of heteroepitaxial structures using perovskite oxides, accessing these multiple degrees of freedom. In this context, we have been studying $SrTiO_3$-based multilayer thin films. $SrTiO_3$ is a wide-band gap ($E_g \sim 3.2$ eV) semiconductor that is readily doped n-type by heterovalent substitution or oxygen vacancies. Despite being a fairly narrow band system ($m^* \sim 3\text{-}5m_o$), the low temperature Hall mobility of bulk-doped crystals can exceed 10,000 cm^2/Vs, in part due to significant screening of the impurity potentials by the lattice arising from a nearby ferroelectric instability. As a result, $SrTiO_3$ remains metallic for carrier densities as low $n \sim 10^{17}$ cm^{-3}. In addition to being a candidate to create low-dimensional, high-mobility electron gases in oxides, there is the intriguing possibility to incorporate superconductivity at similar carrier densities, as $SrTiO_3$ is among lowest density known superconductors in the range of 10^{19}-10^{21} cm^{-3}.

Here we present three different experimental approaches we have pursued using an ultra-high vacuum modification of pulsed laser deposition. In the first case, we have created delta-doped structures on the atomic scale, in which a complete sheet of Sr^{2+} in $SrTiO_3$ has been replaced by La^{3+}. The atomic precision achieved is aided by the unusual kinetics of pulsed laser deposition and the mixed-valence character of titanium, both of which help to overcome the Coulomb repulsion of the charged impurities, which tends to lead to enhanced diffusion. At low temperatures, unusual features appear in the magnetotransport properties, such as an emerging anomalous Hall effect. One speculative explanation is that the electron densities are sufficiently high that correlation effects related to the Mott insulator $LaTiO_3$ become relevant at low temperatures. Secondly, we have fabricated heterostructures in which the oxygen stoichiometry $SrTiO_{3-\delta}$ is modulated by varying the growth kinetics, in which case the dopant profile can be controlled to within a nanometer. Some degree of confinement arises from a significant surface depletion effect, enhanced considerably with reducing temperatures due to the near divergence of the static dielectric constant. Finally, we have used polarization discontinuities at a heterointerface to introduce free carriers in $SrTiO_3$. In several of the above examples, we have attained sufficiently high electron mobility to observe Shubnikov-de Haas magnetoresistance oscillations. Our current challenge is to gain sufficient control at low densities and in confined geometries to achieve a low subband occupation.