Intrinsic Instability of Electronic Interfaces with Strong Rashba Coupling

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January 2013

The recent observation of a two-dimensional (2D) metallic state at the interface of two insulating oxides LaAlO$_3$/SrTiO$_3$ [1] has uncovered a novel class of high-mobility electron gases (EG) which is important for both theoretical and practical prospects. Indeed, these 2DEG exhibit a variety of intriguing properties such as high electron mobility [2], superconductivity [3, 4], magnetism and large magnetoresistance [5]. Moreover, the possibility of tuning these properties by means of external fields makes these materials interesting from a technological point of view.

Various experimental and theoretical works have been devoted to the explanation of these 2DEG, in particular concerning the source of the charge carriers. Two possibilities have been pointed out, which are the introduction of oxygen vacancies and an electronic reconstruction at the interface due to the different polarity of the two oxides. Another issue which attracted attention and which will be of particular interest to us, is the effect of spin-orbit interaction; due to the broken inversion-symmetry, this so-called Rashba spin-orbit (RSO) interaction is expected to be an important piece of the puzzle.

On the other hand, there is increasing experimental evidence that (electron) inhomogeneities play a relevant role in these systems. Not only is the large width of the superconducting transition measured in transport experiments a clear indication of charge inhomogeneity [6, 7], but also magnetometry and tunneling experiments [8, 9, 10, 11] report inhomogeneities on a submicroscopic scale. While impurities, defects and other extrinsic mechanisms surely introduce inhomogeneities, the recent discovery of negative compressibility in a low-density regime [12] provides a stringent demonstration that an intrinsic mechanism (e.g., an effective attraction) is at work to render these 2DEGs inhomogeneous by phase separation even in a perfectly clean and homogeneous system.

In this regard, it was recently shown that the phase separation arises due to Rashba spin-orbit interaction, provided that the electric field determining the interaction strength
Figure 1: Dispersion relation in presence of Rashba spin-orbit interaction.

also controls the electron density [13] (which is the case for the oxide interfaces we have in mind). Let us briefly explain how this phase separation comes about. The dispersion equation relating the electrons energy $E$ to its orbital degree of freedom $k$ reads

$$E_{\pm}(k) = \frac{\hbar^2 k^2}{2m} \pm \alpha k,$$

with $k = \sqrt{k_x^2 + k_y^2}$, (1)

where $m$ is the electron mass and $\hbar$ is Planck’s constant (divided by $2\pi$). The RSO interaction lifts the spin degeneracy of the free electron, leading to a dispersion $E_{\pm}(k)$ with two branches corresponding to opposite spin projections (Figure 1). The minimum energy $E_{\text{min}} = -\frac{\alpha^2}{2\hbar^2}$ is proportional to the squared Rashba constant, which, by assumption, depends on the electron density via the electric field. As a result, the band structure is not rigid, as in conventional systems, but it depends on the band-filling; the higher the electric field is, the greater the Rashba constant and the lower the band minimum are. This may render energetically convenient for the system to attract electrons to have a deeper energy minimum, where more electrons can be accommodated at lower energy. This downward shift of the band bottom may overcome the increase of the Fermi level due to the increased electron density and an overall decrease of the chemical potential may occur, leading to a negative compressibility.

Currently, we investigate the possible occurrence of a phase separation for systems at finite temperature, finite (in-plane) magnetic field and an applied gate-voltage and we extend the single-electron model to take into account electron-electron and electron-phonon interactions.

My PhD thesis will be devoted to the study of the various aspects of the phase separation outlined above. In a first step, this will be mainly done by means of numerical simulation, because it yields acceptable results in a short time and can be rather easily extended to incorporate additional physical features. Once the mechanisms are proven
to work and well understood, one might envisage a more analytical approach putting
the numerical results on a stronger theoretical ground.

References

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