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Limitations to the room temperature mobility of two- and three-dimensional electron liquids in SrTiO₃

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We analyze and compare the temperature dependence of the electron mobility of two- and three-dimensional electron liquids in SrTiO₃. The contributions of electron-electron scattering must be taken into account to accurately describe the mobility in both cases. For uniformly doped, three-dimensional electron liquids, the room temperature mobility crosses over from longitudinal optical (LO) phonon-scattering-limited to electron-electron-scattering-limited as a function of carrier density. In high-density, two-dimensional electron liquids, LO phonon scattering is completely screened and the mobility is dominated by electron-electron scattering up to room temperature. The possible origins of the observed behavior and the consequences for approaches to improve the mobility are discussed. © 2015 AIP Publishing LLC.

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FIG. 1. (a) Temperature dependence of the Hall mobility ($\mu$) of SrTiO$_3$ doped with La to a carrier density of $8 \times 10^{18}$ cm$^{-3}$ (from Ref. 21). The solid line is a fit to Eq. (1), with $\mu_{LO} = \frac{2}{1 + 0.1}$ and $\mu_{LO}$ as given by Eqs. (2) and (3), while the dashed lines show the temperature dependence of the terms in Eq. (1) obtained from the fit. (b) and (c) Extracted parameters $x$ and $\omega_{LO}$ from fits to the samples with different doping concentrations ($N$). The individual fits are shown in the supplementary material.30 (d) Comparison of the measured room temperature mobility (solid circles), $\mu_{ee}$ (diamonds), and $\mu_{LO}$ (squares) calculated using the extracted fit parameters, and $(\mu_{ee} + \mu_{LO})^{-1}$ (hexagons). The close agreement between the measured $\mu$ and $(\mu_{ee} + \mu_{LO})^{-1}$ shows that the room temperature mobility is controlled by electron-electron and LO phonon scattering terms, with a crossover in the dominant contribution near $N \sim 6 \times 10^{18}$ cm$^{-3}$. The solid line in Fig. 1(a) shows a fit using Eqs. (1)–(3), which accurately describes the experimental data. The fit parameters were $\mu_0$, $x$, and $\omega_{LO}$. In SrTiO$_3$, carriers are believed to couple strongly to two LO phonon modes and the value for $\omega_{LO}$ determined here is an average, effective value. Fits for the more highly doped samples are shown in the supplementary material and yield similarly good descriptions. Figures 1(b) and 1(c) show the results for $x$ and $\omega_{LO}$ as a function of $N$. As $N$ increases, $\omega_{LO}$ and $x$ both increase. As a result, $\mu_{LO}$ increases while $\mu_{ee}$ decreases and the total mobility becomes increasingly limited by electron-electron scattering. This is summarized in Fig. 1(c), which shows $\mu_{ee}$ and $\mu_{LO}$ calculated at room temperature using the extracted values for $x$ and $\omega_{LO}$, the total mobility calculated using these two terms, and the experimentally measured Hall mobility. At $N \sim 6 \times 10^{18}$ cm$^{-3}$, the electron-phonon scattering limited regime crosses over to an electron-electron scattering limited regime; as a result, the mobility remains $<10$ cm$^2$ V$^{-1}$ s$^{-1}$ for all $N$. The increase of $\mu_{LO}$ with $N$ is in agreement with first-principles calculations,11 where it has been shown that the electron-phonon scattering rates decrease away from the Brillouin zone center. Thus with increasing $N$, the Fermi surface enlarges, the scattering rate becomes smaller, leading to an increase in $\mu_{LO}$.

The results shown in Fig. 1 confirm earlier results that electron-electron scattering must be accounted for in describing the temperature-dependence of the mobility of SrTiO$_3$, and furthermore show that it becomes the limiting mechanism at high doping. It is well known that for simple metals with a single conduction band, electron-electron scattering leads to resistance only for Umklapp processes at linear order transport theory.27,31 This is due to the fact that the total crystal momentum is conserved in an electron-electron scattering event for normal (non-Umklapp) processes. In SrTiO$_3$, the increased electron-electron scattering rate at high doping [Fig. 1(b)] can also be attributed to Umklapp processes. With increasing $N$ the Fermi surface expands, reaching closer to the Brillouin zone boundaries, enabling Umklapp scattering. Furthermore, when there are multiple conduction bands, as is the case for SrTiO$_3$,32,33 electron-electron scattering can proceed through both intraband and interband transitions. For an interband scattering event, the total current can change via transfer of electrons between bands with different effective masses, leading to resistance from electron-electron scattering even for normal processes, in addition to Umklapp ones.34 This leads to an increased electron-electron scattering rate compared to simple metals. In addition, short-range Coulomb interactions are strong for the conduction bands derived from the localized 3d orbitals of Ti, which also leads to an enhancement of electron-electron scattering.2 These interactions increase with $N$ (as the probability of two electrons occupying the same site increases).

Figure 2 shows the Hall mobility as a function of temperature for the 2DELs in structures with different SrTiO$_3$ thicknesses. As shown by the dashed lines, the mobility can be completely described over the entire temperature range up to room temperature as $\mu^{-1} = \mu_0^{-1} + \mu_{ee}^{-1}$. Thus, unlike for bulk doped samples, there is no detectable LO phonon
scattering contribution in the 2DELS. The absence of LO phonon scattering explains the slightly larger room-temperature mobility in the 2DELS. The inset in Fig. 2 shows \( \alpha \) as a function of SrTiO\(_3\) thickness. For the thinnest layers, the three-dimensional carrier density in the 2DEL is increased (the layer width is substantially smaller than the spatial extent of the 2DEL) and the strength of electron-electron scattering \((\alpha)\) is increased.

The results indicate a complete screening of the LO phonon mode in the 2DELS. In addition to the screening by the large density of carriers in the 2DEL, electronic screening also depends on the density of states (DOS). Confinement in a 2DEL increases the DOS at the Fermi level. An indicator of a substantial increase of the DOS in GdTiO\(_3/\)SrTiO\(_3\) 2DELS is the observed itinerant ferromagnetism, as it is required to satisfy the Stoner criterion to cause spin polarization in the conduction bands. Once the conduction electrons screen the ionic potentials effectively, there is no long range Coulomb interaction that splits the LO and TO mode in the 2DELS. In addition to the screening by the three-dimensional carrier density in the 2DEL, electronic screening \((\alpha)\) is increased.

**Fig. 3.** Room temperature mobility as a function of the extracted electron-electron scattering parameter \( \alpha \) for the 2DELS (diamonds) and three-dimensional electron gases (squares). The dashed line is calculated according to \( \mu^{-1} = aT^2 \). The mobility of the three-dimensional electron gases falls below the dashed line due to the significant contribution of LO phonon scattering, which is absent in the 2DELS. The extremely confined 2DELS (two right-most data points) fall below the line due to contributions from interface roughness scattering even at room temperature.

In summary, we have shown that the room temperature mobility in high-carrier-density 2DELS in SrTiO\(_3\) is not limited by LO phonon scattering, in sharp contrast to bulk, doped SrTiO\(_3\). To develop approaches to improve the mobility in the 2DELS, a quantitative, theoretical understanding of contributions to \( \alpha \) in SrTiO\(_3\) 2DELS must be developed. The results emphasize that the transport physics of 2DELS in complex oxides is significantly different from that of conventional semiconductors, where electron-electron scattering only plays a minor role and electron-phonon scattering is the dominant mechanism limiting the room temperature mobility.

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