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Optically excited multi-band conduction in LaAlO$_3$/SrTiO$_3$ heterostructures

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The low-temperature resistance of a conducting LaAlO$_3$/SrTiO$_3$ interface with a 10 nm LaAlO$_3$
film decreases by more than 50% after illumination with light of energy higher than the SrTiO$_3$
band-gap. We explain our observations by optical excitation of an additional high mobility electron
channel, which is spatially separated from the photo-excited holes. After illumination, we measure
a strongly non-linear Hall resistance which is governed by the concentration and mobility of the
photo-excited carriers. This can be explained within a two-carrier model where illumination creates
a high mobility electron channel in addition to a low mobility electron channel which exists before
illumination. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4790844]
over time of the total power incident on the sample, normalized with the energy of a single photon. The solid circles (left axis) show the resistance change of the sample, normalized by the number of incident photons, at each photon energy. The most drastic change occurs when the photon energy is higher than the STO band gap, shown as the vertical dashed line in the figure.

In order to explain these results, we propose the generation of additional, photo-excited carriers, as depicted in the inset of Fig. 1: Illuminating either the bulk STO (control sample) or the LAO/STO heterostructure with photon energy higher than the band gap of STO creates electron-hole pairs in the STO substrate. In the case of bulk STO, the photo-excited electrons in the empty conduction band do not persist for a long time and recombine very quickly with holes in the valence band, or through other recombination centres. For the case of LAO/STO heterostructure, the photo-excited electrons move to the interface potential well, where the holes remain trapped in the substrate. Owing to this spatial separation, electron and hole wavefunctions do not overlap, and direct optical recombination is suppressed, leading to a persistent resistance change.

For the LAO/STO heterostructure, the interface potential lifts the degeneracy of the STO bulk bands (Ti-3d xy, yz, and xz orbitals), and a further formation of 2D subbands is expected due to spin-orbit coupling and the internal electric field due to growth of LAO layers. The 2D interface potential well gives a multi-subband character to the STO conduction band at the interface of LAO/STO. Owing to this multi-subband structure of the interface, we propose that the photo-excited carriers occupy an initially unoccupied subband with a high mobility.

To study the nature of the persistent photo-excited carriers, we have performed magnetotransport experiments after illumination with an increasing total number of photons \( N_{tot} \), controlled with neutral density filters, at a constant photon energy of 3.65 eV. In Fig. 3(a), we show the Hall resistance \( R_{xy} \) as a function of the applied magnetic field \( B \) at 4.2 K, before illumination and after illuminating with four different values of photon energy.

FIG. 1. Sample resistance as a function of time during the illumination with photons of energy from 1.44 to 3.65 eV at 4.2 K. Each change in the photon energy results in a pronounced step in the sample resistance; the photon energies, in eV, are shown beside each of the steps. Note the break on the time-axis showing the persistence of the resistance change. The inset shows a schematic band diagram (CB—conduction band, VB—valence band, and \( E_F \)—Fermi-level) for a LAO/STO heterostructure under illumination and presuming an internal potential build up in the LAO.

FIG. 2. Total number of photons at the sample as a function of photon energy is shown in open circles (right axis). Normalized sample resistance as a function of the energy of illuminating photons is shown in solid circles (left axis). The connecting lines are a guide to the eye.

FIG. 3. (a) Hall resistance data as a function of the applied magnetic field, for illumination with different values of \( N_{tot} \) with energy of 3.65 eV at 4.2 K (open symbols). Solid lines: The two-band model fits to the experimental data. (b) (longitudinal) Magnetoresistance data as a function of the applied magnetic field and (c) carrier concentration of the second, high mobility band for illumination with different values of \( N_{tot} \).
of \(N_{\text{tot}}\) (open symbols). The corresponding (longitudinal) magnetoresistance is shown in Fig. 3(b). Without any illumination, a linear Hall resistance and a small negative magnetoresistance are observed, in agreement with earlier observations on a similar sample. After illumination, a distinctly non-linear Hall resistance and a large positive magnetoresistance appear.

We describe the linear Hall resistance using the conventional single-carrier model and extract the carrier concentration \(n = B/R_{xy}\) and mobility \(\mu = 1/\rho_0 e n\) from the slope of the linear fit to the data—the fit is shown as a solid line in Fig. 3(a), where \(\rho_0\) is the zero-field sheet resistance and \(e\) is the electronic charge. This yields a carrier density \(n_1 = 8.9 \times 10^{13} \text{cm}^{-2}\) and a mobility \(\mu_1 = 3 \text{cm}^2/\text{Vs}\). This very low carrier mobility is similar to values previously observed in LAO/STO samples with comparable LAO layer thickness.\(^{3,30}\)

In contrast, the non-linear Hall resistance after illumination cannot be explained within a single-carrier model but rather suggests a multi-channel system. A similar non-linear behavior of the fits was insensitive to small variations in the illumination, and obtained. For the higher values of \(N_{\text{tot}}\), we model the Hall resistance data after illumination.

The results of our two-band analysis are shown in Fig. 3(a) as solid lines. We fitted the non-linear Hall resistance for \(N_{\text{tot}} = 8.6 \times 10^{11}\), using \(n_2\) and \(\mu_2\) as fit parameters, and with fixed values of \(n_1 = 8.9 \times 10^{13} \text{cm}^{-2}\) and \(\mu_1 = 3 \text{cm}^2/\text{Vs}\) (as extracted from the linear Hall resistance before illumination): values of \(n_2 = 0.5 \times 10^{10} \text{cm}^{-2}\) and \(\mu_2 = 1200 \text{cm}^2/\text{Vs}\) were obtained. For the higher values of \(N_{\text{tot}}\), we found that the quality of the fits was insensitive to small variations in \(\mu_2\) around this value of \(1200 \text{cm}^2/\text{Vs}\). We therefore fixed \(\mu_2 = 1200 \text{cm}^2/\text{Vs}\) and used only \(n_2\) as a fit parameter for the higher values of \(N_{\text{tot}}\). The values of \(n_2\) extracted in this way are shown in the Fig. 3(c). For the highest value of \(N_{\text{tot}}\), a good fit to \(R_{xy}\) required a slightly increased value of \(n_1\) from \(8.9 \times 10^{13} \text{cm}^{-2}\) to \(1.19 \times 10^{14} \text{cm}^{-2}\), with an unchanged value of \(n_2\) (as shown in Fig. 3(c)).

This two-band analysis of the Hall resistance strongly suggests that we populate a second, high mobility electron channel by illumination above the STO band-gap. This observed relatively high mobility (1200 cm²/Vs) of the persistently photo-excited electrons is similar to the values previously observed in reduced or non-stoichiometric bulk STO.\(^{3,34-36}\) The fact that we see comparable high mobility values for photo-excited carriers suggests that the influence of interface defects is not so crucial in this case. A surface morphology study of the STO [001] substrate using an atomic force microscope, prior to growth of the LAO layer, did not reveal any macroscopic defects.

In summary, we have measured magnetotransport in a LAO/STO heterostructure, with a 10 nm LAO film, after illumination with selective photon energy. When the photon energy exceeds the STO band gap, the low-temperature resistance decreases by more than 50% and remains persistent at the lower value. We explain this effect in terms of optical excitation of an additional high mobility electron channel, which is spatially separated from the photo-excited holes, and confirm the presence of a second conducting electron band through measurement of a strongly non-linear Hall resistance after illumination. A two-carrier description of the Hall resistance data after illumination shows one low mobility (3 cm²/Vs) band with a high carrier density (\(\approx 10^{13} \text{cm}^{-2}\)) corresponding to the original conduction band present before illumination, and one persistently photo-excited high mobility (1200 cm²/Vs) band with a low carrier density (\(\approx 10^{10} \text{cm}^{-2}\)). We suggest that these persistently photo-excited carriers occupy one of the interface 2D subbands in STO, where these carriers have relatively higher mobility than the existing low mobility carriers without illumination.

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