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ABSTRACT
The two-dimensional electron system (2DES) formed at the interface of LaAlO$_3$ (LAO) and SrTiO$_3$ (STO), both band insulators in bulk, exhibits properties not easily attainable in conventional electronic materials. The extreme shallowness of the 2DES, only a few nanometers below the surface, opens up unique possibilities such as tunneling spectroscopy, local electronic sensing, and in situ patterning by manipulating the surface properties. It is particularly tempting to manipulate the charge carriers with surface acoustic wave (SAW) phonons, which are confined to the surface. However, the absence of intrinsic piezoelectricity in both LAO and STO complicates the electric generation of SAWs, as well as the induction of an acoustoelectric current. Here, we present robust acoustoelectric coupling between SAWs and the LAO/STO 2DES by using electrostriction in STO, induced by a dc electric field. Electromechanical coupling to the carriers is provided by phonon-induced modulation of the 2DES potential well, leading to SAW-induced carrier transport. The ability to control charge carriers with SAWs brings the versatile LAO/STO 2DES into reach of quantum acoustics, opening possibilities to study the interplay of nanoscale mechanical waves and the rich physics exhibited by nonpiezoelectric complex oxides, including superconductivity, magnetism, and correlated insulator states.

Surface acoustic waves (SAWs) are periodic surface deformations in the form of acoustic waves traveling along the surface of a solid, typically localized on the order of a wavelength near the surface. A common way of generating SAWs is by applying an RF signal to an interdigital transducer (IDT) on a piezoelectric material. When traveling in a piezoelectric material, SAWs are accompanied by a piezoelectric potential wave. Free charge carriers may interact with this moving piezoelectric field, and get dragged along, generating a current. This is known as the acoustoelectric (AE) effect and has been observed in different semiconductors by electrical and optical detection methods. Particularly, the two-dimensional electron system (2DES) at the AlGaAs/GaAs interface has been explored for acousto(opto)electronics, owing to intrinsic piezoelectricity, high carrier mobility, and direct bandgap. In order to electrically generate SAWs and manipulate charge carriers with a traveling piezoelectric potential wave in a nonpiezoelectric semiconductor, such as silicon, it is necessary to incorporate a thin film of a piezoelectric material, such as ZnO or AlN, underneath the IDTs and close to the free carriers. Graphene and transition metal dichalcogenides (TMDs), such as MoS$_2$ and WSe$_2$, have been deposited on strongly piezoelectric substrates, such as LiNbO$_3$, to carry out AE experiments in 2DESs. Mechanical control of charge carriers by SAWs has not been demonstrated at complex-oxide interfaces, in spite of their attractive electronic properties. The LaAlO$_3$ (LAO)/SrTiO$_3$ (STO) 2DES offers a particularly interesting platform for studying acoustoelectric charge transport. A carrier mobility exceeding 10,000 cm$^2$ V$^{-1}$ s$^{-1}$ at cryogenic temperatures and magnetic effects at very low temperatures were reported. Implementing AE control of charges at the LAO/STO interface is a challenge, however, because neither LAO nor STO are piezoelectric. Deposition of a piezoelectric thin film on top of LAO/STO could, in principle, solve the problem. However, this approach introduces another challenge, as the 2DES could be degraded when it is exposed to deposition of an additional top layer.

Piezoelectricity refers to electric polarization due to uniform strain and arises in crystals that lack inversion symmetry. At room temperature, single-crystal STO is a centrosymmetric, cubic dielectric that does not exhibit piezoelectricity, due to the central position of the Ti$^{4+}$ cation in the lattice, see Fig. 1(a). However, the desired coupling between a RF electric field and a lattice deformation, necessary for the
generation and detection of SAWs with IDTs, may be achieved either by flexoelectricity,24 i.e., electric polarization resulting from a strain gradient, or by electrostriction,25 i.e., lattice deformation under the application of an electric field. By applying a dc electric field to STO, the Ti$^{4+}$ cation is displaced and the cubic symmetry is broken,26 see Fig. 1(b). Such a distortion of the lattice (electrostriction) generates electric dipoles, and consequently, a polarization in the crystal is produced.27,28 By using dc-field-induced piezoelectricity, it has been shown that it is possible to generate and detect SAWs with IDTs on STO.29 Here, we make use of this dc-field-induced piezoelectric effect to demonstrate SAW-driven acoustoelectric transport at the LAO/STO interface. The associated coupling between SAWs and charge carriers may be, in principle, extended into the quantum regime, for example, via quantization of the acoustoelectric current or coupling quantized SAW phonon modes to electronic quantum states.

The device layout is shown in Fig. 1(c) (see the supplementary material for the details of sample fabrication and the experimental setup). The nominally identical IDTs are designed in a delay-line configuration, and both IDTs can be used for generating and detecting SAWs. The 2DES is patterned into a Hall bar, enabling AE transport and Hall-effect measurements on the same device.

The SAW transmission between IDT1 and IDT2 was characterized by means of S-parameter analysis, and the corresponding AE current was measured at room temperature and at 150 K, in vacuum and in the dark, see Fig. 2. In accordance with previous work,30 upon cooling the system below 150 K, we first observed a gradual and then an abrupt suppression of the electrostrictive generation of SAWs at $\sim$105 K, most likely related to the structural phase transition of STO from cubic to tetragonal. Therefore, in the following, we do not consider temperatures lower than 150 K, at which both SAW transmission and AE current show a broad maximum. In order to enable similar experiments at lower temperatures, one could make use of additional piezoelectric materials to generate SAWs instead of relying on electrostriction in STO; this is, however, out of the scope of the present work. From the Hall measurements, we extract a charge carrier mobility varying from 1.92 cm$^2$/V s at room temperature to 16.91 cm$^2$/V s at 150 K (Fig. S3 in the supplementary material).

A dc bias voltage was applied initially to only IDT1 in addition to the ac voltage supplied by the vector network analyser (VNA). The dc voltage was increased in 10 V steps, starting from 0 V up to 50 V, above which we observed dielectric breakdown of the device. As shown in Fig. 2(a) (red curve), when a dc bias of 50 V and an RF input...
power of 0 dBm were applied to IDT1 at room temperature, a weak SAW transmission signal is observed at \( \approx 438 \) MHz, corresponding to the expected SAW resonance frequency (SAW transmission vs dc bias is shown in Fig. S2 in the supplementary material). This shows that some conversion of the mechanical deformation to an electric signal is achieved at IDT2 without electrostriction induced by a dc voltage applied to IDT2. We ascribe this to the flexoelectric effect caused by the strain gradient at the SAW STO surface. The SAW transmission increased strongly after a dc bias was also applied to IDT2, providing electrostriction at both the sending and the receiving IDT [Fig. 2(a)].

The same measurements were repeated at 150 K, see Fig. 2b. Although the transmission background level was the same at 150 K, the SAW transmission was much larger than that at room temperature. This is consistent with previous reports \(^{25,27}\) and was ascribed to the quadratic dependence of the electrostriction-induced piezoelectric strain coefficient on the dielectric permittivity. \(^{25}\) The strong temperature dependence of the latter \(^{11}\) in STO leads to a much higher conversion efficiency of RF power into SAWs at the IDTs at lower temperature. In part, the higher SAW transmission signal could also be related to the reduced interaction of the thermally excited phonons with the acoustic waves in the crystal at lower temperatures, known as the Landau-Rumer mechanism, \(^{25}\) resulting in reduced SAW attenuation during transit between input and output IDT. Additionally, we note that the SAW resonance frequency shifts to higher frequency at lower temperature. We attribute this observation to the temperature dependence of the phonon frequencies in STO and the associated increase in sound velocity. \(^{25,27,30}\)

The interaction mechanism between SAWs and electrons in the LAO/STO 2DES was investigated by studying the acoustoelectric current, \( I_{AE} \), and voltage, \( V_{AE} \). When SAWs propagate through the 2DES, the crystal is deformed by the associated strain wave, breaking the cubic symmetry of the STO crystal accordingly [Fig. 1(b)]. The electric dipole resulting from the symmetry breaking produces an electric field, which couples to the free charges in the 2DES. As mentioned in the introduction, propagating SAWs can produce acoustic charge transport by dragging electrons with this electric field. Upon effectively shorting the conducting channel with a current measurement unit, as shown in Fig. 1(c) in red (see the supplementary material for details), we can detect a dc AE current. Under open circuit conditions, a dc voltage builds up instead, to the point where the back-flow of charges compensates the carrier drag by the SAWs. In Fig. 2(c), room-temperature AE current measurements are shown. Initially, IDT1 was excited with no dc bias applied, such that the generation of SAWs is negligible. We did not observe any \( I_{AE} \) at (or near) the resonance frequency of \( \approx 438 \) MHz, as expected. Subsequently, a dc bias of 40 V was applied to IDT1, and a clear \( I_{AE} \) peak of a few pA appeared at \( \approx 438 \) MHz. The very low \( I_{AE} \) is ascribed to the low 2DES carrier mobility at room temperature. To verify whether the signal stems from the AE effect, we switched the input from IDT1 to IDT2. When SAWs propagate in the opposite direction, the sign of \( I_{AE} \) must also change as the electrons are now transported in the opposite direction. Indeed, Fig. 2(c) shows this sign reversal.

At 150 K, both the SAW transmission and the 2DES carrier mobility are higher than those at room temperature, which should enhance the AE current. \(^{11}\) This is confirmed in Fig. 2(d), where \( I_{AE} \) is about an order of magnitude larger at 150 K than at room temperature. Moreover, we find that \( I_{AE} \) increases linearly with RF input power (Fig. S4 in the supplementary material), in accordance with theory. \(^{33}\) As a larger input power excites SAWs with increased amplitude, this results in stronger electric fields accompanying the SAWs and thus a stronger interaction with the charges in the 2DES. Similar to room-temperature \( I_{AE} \) measurements, we generated SAWs from both IDTs, and the sign of the current changed when the SAW propagation direction was reversed. We also found that \( I_{AE} \) linearly scales with the RF input power in the same way for both IDTs (Fig. S4 in the supplementary material). A final essential observation in Fig. 2 is that the shift in the SAW resonance frequency from \( \approx 438 \) MHz to \( \approx 445 \) MHz when cooling down is accompanied by the same shift in the frequency at which \( I_{AE} \) is generated. Further characterization of \( I_{AE} \) vs dc bias was performed to exclude spurious effects (Fig. S1 in the supplementary material).

The acoustoelectric voltage was also measured at 150 K. The measurement schematic is given in Fig. 1(c), in green. In Fig. 3(a), \( V_{AE} \) is presented as a function of frequency and RF input power. Similar to \( I_{AE} \), \( V_{AE} \) also scales with the RF input power, and its polarity is inverted when the input IDT is exchanged. Figure 3(b) shows the dependence of \( V_{AE} \) on the channel length. Larger values of \( V_{AE} \) were measured for the increasing distance between the contacts, in accordance with Ohm’s law and the condition that the back-flow of charges must equal the acoustoelectric current for an open circuit. As a control experiment, we also measured \( V_{AE} \) between contacts 2 and 6 at the same distance from IDT1, but on opposite sides of the Hall bar. As shown in Fig. 3(b) (green curve), no \( V_{AE} \) was measured, as expected when the voltage is of acoustoelectric origin and not due to spurious effects.

The results shown above establish acoustoelectric coupling between SAWs generated in STO and charge carriers residing at the LAO/STO 2DES, enabling the generation of currents on the order of 10 pA in a 10-\( \mu \)m-wide channel and voltages on the order of 1\( \mu \)V over distances of a few hundred micrometers. While the generation and detection of SAWs in STO using IDTs rely on electrostriction, the acoustoelectric coupling in the conducting channel manifests itself in the absence of any external bias potentials. This shows that the mechanical waves must produce a significant potential modulation and associated electric field at the LAO/STO interface, resulting in the
observed drag of electrons, which is clearly absent in undoped STO. Quantitative analysis of the thus-obtained acoustoelectric current is difficult because the traditionally used models use bulk material parameters that are not a priori applicable here, while the acoustoelectric coupling constant of the LAO/STO interface is unknown. In principle, the latter could be determined experimentally, by measuring the sound velocity with or without depletion of carriers from the 2DES, which would require devices that enable near complete depletion of the channel. Here, we give an order-of-magnitude estimate of this parameter from an acoustoelectric transport model that has been applied to other 2DESs, e.g., in GaAs-based structures (see the supplementary material). By substituting parameters that are either determined experimentally in this work or taken from the literature, we find an acoustoelectric coupling constant $K_{ac}$ of $3.1 \times 10^{-5}$ at room temperature and $2.5 \times 10^{-5}$, at 150 K. Considering the nonpiezoelectric nature of the LAO/STO interface, having an acoustoelectric coupling coefficient, $K_{ac}$, on the order of $10^{-5}$, which is about ten times smaller compared to that of (weakly) piezoelectric GaAs, but sufficient to drag charge carriers along with the SAWs, confirms that LAO/STO 2DES can be employed to realize SAW-assisted quantum electronic devices and networks. Manipulating the LAO/STO 2DES by SAW phonons instead of conventional electrical or magnetic control methods offers an additional degree of freedom and provides a promising route to develop fundamental insights and broaden the application horizon. For example, studies of the interplay of nanoscale mechanical waves and superconductivity, magnetism, and correlated insulator states could be undertaken. Our approach of manipulating charge carriers with SAWs may also be considered to be employed in other nonpiezoelectric complex oxide systems.

In conclusion, our results establish that SAWs can induce currents and voltages in the 2DES at the LAO/STO interface. The signals are enhanced by boosting the mobility of the 2DES or by generating stronger SAWs. The latter option may not require high(er) dc bias voltages on the IDTs; instead, modification of the IDTs may help to increase SAW transmission by preventing internal reflections inside the IDT or backward reflections of the transmitted signals from the receiver IDT. For narrower conduction channels and/or quantum point contacts, single-electron acoustoelectric devices may be realized. Our results clearly show that acoustoelectric devices, in which SAWs control charge transport at LAO/STO interfaces, are within reach.

See the supplementary material for elaborate experimental details, corrections made to the measured acoustoelectric current, calculations of the electromechanical coupling constant of the LAO/STO 2DES from an acoustoelectric current model, measurements of the acoustoelectric current and SAW transmission vs dc bias on the input IDT, electrical characterization of the LAO/STO 2DES, measurements of the acoustoelectric current vs RF input power, and supplementary references.

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