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One dimensional electron gas at the $LaAlO_3/SrTiO_3$ interface and its transport properties

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Quasi-one-dimensional electron gases (q1DEGs) have been obtained by fabricating $LaAlO_3$ nanowires, using the technique of electrostatic spinning plus post annealing, above TiO_2-terminated $SrTiO_3$ substrate. The q1DEG exhibits an electronic transport behavior of variable range hopping with the one dimension characteristic. Visible light illumination produces a strong effect on transport process, depressing the resistance of the q1DEG by a factor up to 8. As expected, gating effect is weak at relative high temperatures, $\sim$3.2% at 150 K and 1.5% at 300 K under a back gate of 200 V. Aided by light illumination, however, the gating effect is 35-fold amplified, and the resistance increases under not only negative gates but also positive gates, different from the normal gating effect without illumination. Possible explanations for these phenomena are given. *Published by AIP Publishing.*
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Complex oxide interfaces have been the focus of intensive studies in recent years because of the emergent phenomena associated with interlayer coupling, spatial confinement, and charge/orbital reconstruction. This makes the interface systems distinct from bulk materials,[1] exhibiting a plenty of interesting effects, such as the enhanced ferromagnetic order for the $La_{0.7}Sr_{0.3}MnO_3/BaTiO_3$ superlattices,[2] the antiferromagnetic interlayer coupling for the $La_{0.7}Sr_{0.3}MnO_3/SrRuO_3$ (SRO) bilayers,[3] and the distinct magnetic order in paramagnetic layers for the $YBa_2Cu_3O_{7-\delta}/La_{0.7}Ca_{0.3}MnO_3$[4–6] and $LaNiO_3/LaMnO_3$ superlattices.[7] In addition to these, the quasi-two-dimensional electron gas (q2DEG) at the $LaAlO_3/SrTiO_3$ (LAO/STO) interface is of special interest in a sense it presents a distinct platform for strong correlated electrons. In this kind of system, diverse behaviors such as two-dimensional superconductivity,[8,9] two-dimensional ferromagnetic order,[10–12] and the coexistence of the superconductivity and ferromagnetism[13] have been observed. Due to the low dimensionality, the gating effect is strong.[14] Combined with photo excitation, it yields a strong tuning to the physical properties of the q2DEG.[15]

There are also attempts to fabricate one-dimensional electron gas (q1DEG) at the LAO/STO interface. By growing a tiled structure of insulating two-dimensional LAO/STO interfaces composed of alternating one and three LAO unit cells, Ron and Dagan[16] obtained conducting nanowires at the border of two LAO strips. For this system, a quantized conduction is observed when sweeping gate field. Basing on the technique of photolithography, Ron *et al.*[17] further fabricated a single LAO nanowire, $\sim$70 nm in width, above STO, and studied its transport behaviors at ultralow temperatures. The most important discovery is the signature of domains with opposite magnetization. Basing on the technique of silicon nanostencils, Azimi *et al.*[18] prepared LAO/STO nanowires with the width down to 150 nm, and observed a strong gating effect in the temperature range below 50 K. Obviously, the q1DEG owns distinct characteristics that are absent in q2DEG, and therefore deserves further studies.

Here we presented a feasible approach for the preparation of the LAO/STO q1DEG basing on the electrostatic spinning rather than the complex micro fabrication technique, and systematically studied the transport behaviors and their responses to photo exciting and field gating. We observed a variable-range hopping (VRH) behavior of the one-dimensional characteristic and its enhancement by light illumination. Particularly, the gating effect is 35-fold amplified by photo excitation and, interestingly, positive and negative back gates produce similar effects for the q1DEG in light.

As electrode, a 50-nm-thick $SrRuO_3$ (SRO) film was first deposited on a TiO_2-terminated (001)-STO substrate ($5 \times 5 \times 0.5 mm^3$) by pulsed laser deposition (Substrate temperature is 680 °C and oxygen pressure is 15 Pa) and then patterned into four parallel strips with a separation of 20 μm using the conventional UV-lithographic and etching technique. A single LAO nanowire was synthesized by the technique of electrostatic spinning. The precursor was a mixture of appropriate lanthanum (III) nitrate hydrate ($La(NO_3)_3 \cdot 6H_2O$), aluminum nitrate nonahydrate ($Al(NO_3)_3 \cdot 9H_2O$), N, N- dimethylformamide (DMF), and polyvinylpyrrolidone, and deionized water, which has been continuously stirred for 12 h at room temperature to get homogeneous solution. The operation voltage was 12 kV and the distance between injection needle and grounded plate was 15 cm. After transferred to the substrate with the four SRO strips, the single nanowire suffered from two successive post annealing, first at 450 °C for 3 hs in air and then at 700 °C for 15 min in high vacuum ($\sim 10^{-4}$ Pa). For comparison, a LAO film was also prepared above the STO substrate by spin coating and post annealing as for the nanowire.

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Surface morphology of the nanowire was measured by atomic force microscope (Seiko SPA400). The crystal structure of the LAO film was measured by a Bruker diffractometer (D8 Discover, Cu K_α radiation). The electric characteristics of the nanowire were measured, using the four-probe technique with an applied current of 10 μA, in the temperature range from 150 K to 300 K by a Keithley 2611 SourceMeter. The temperature was controlled by a closed cycling cryostat. The spot size of the laser beam was ~2.8 mm in diameter, completely covering the nanowire between two inner electrodes.

Fig. 1(a) shows an AFM image of the LAO nanowire. The nanowire is uniform in width, forming an angle of ~30° with the terrace step of the STO surface. Fig. 1(b) is a line profile of the nanowire. It looks like a distorted half ellipse, ~160 nm in width and ~76 nm in height. The crystal structure of the nanowire cannot be directly measured by X-ray diffraction (XRD). Using spin coating technique, we prepared a LAO film on STO following exactly the same procedures for the nanowire. XRD analysis shows that the LAO film is epitaxially grown, owning an out-of-plane lattice parameter of 3.770 Å. This value is considerably smaller than that of the single crystal LAO (3.795 Å), and could be an indication of in-plane lattice expansion of the LAO film. In general, the nanowire may be formed in a similar structure as the film.

Fig. 2(a) shows the resistance (*R*) of the LAO nanowire as a function of temperature (*T*), measured through the four SRO electrodes underneath LAO. Finite resistance is detected from room temperature down to 50 K. It is $\sim 7.2 \times 10^6 \Omega$ at 300 K and $\sim 1.4 \times 10^{10} \Omega$ at 50 K. Below 50 K, a tendency towards saturation appears, which may be unreliable since the resistance value is already beyond the scope of our measurement system. For comparison, we measured the resistance of a LAO nanowire grown on a LAO substrate following exactly the same procedure as those for the LAO/STO nanowires, and found that the LAO/LAO nanowire remains insulating after vacuum annealing. This means that the conduction behavior observed above cannot be ascribed to the LAO nanowire itself. We further checked the STO substrate suffering from vacuum annealing, and found that it is also insulating. Based on these results, we can safely say that the finite conduction of the LAO/STO nanowire comes from the LAO/STO interface, i.e., the quasi-one-dimensional electron gas (q1DEG) at the interface. To compare with q2DEG, the line resistance of the q1DEG is converted into sheet resistance. According to Fig. 1(b), the q1DEG is ~160 nm in width. Basing on the formula $R_S = R*W/L$, we obtained an equivalent sheet resistance. It is ~57 kΩ/□ at room temperature and ~110 800 kΩ/□ at 50 K, where *W* is the line width of the nanowire, and $L = 20\,\mu$m, is the separation between two middle electrodes. The first value is comparable to the quantum of resistance $h/e^2 = 25.8$ kΩ but much larger than that of the conventional q2DEG formed at the LAO/STO interface obtained via pulsed laser deposition.[19] These results show that sol-gel technique is a feasible one for the preparation of the interface electron gas. Possibly, the interfacial oxygen in the STO side is rubbed by LAO when annealing the nanowire in vacuum since LAO is much more stable than STO. This technique has advantages because of the absence of plasma bombardment that may result in imperfect interfaces.

A further analysis shows that the high temperature range of the *R-T* curve (above ~143 K) can be well described by the formula of variable-range hopping (VRH) for the one-dimensional system, $R = R_0 \exp[(T_0/T)^{1/2}]$ (Fig. 2(b)), adopting the fitting parameters of $R_0 = 384.1\,\Omega$ and $T_0 = 28247.5$ K. We also tried to fit the *R-T* relation to $R = R_0 \exp[(T_0/T)^{1/3}]$ which is expected by a q2DEG,[19] and the agreement is not satisfactory

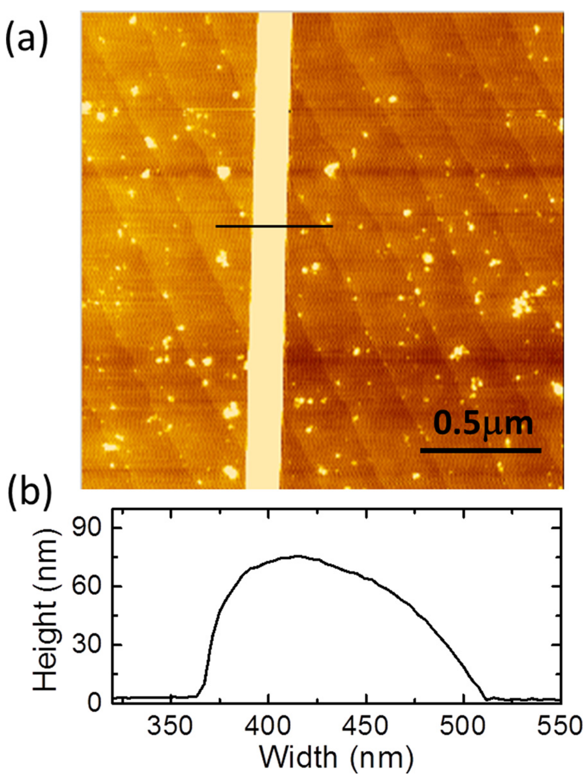


FIG. 1. (a) AFM image of the LAO nanowire grown on TiO_2-terminated STO substrate, fabricated by the technique of electrostatic spinning and post annealing. The nanowire is uniform in diameter, with a smooth surface. (b) Line profile of the nanowire, recorded along the black line marked in the image. It looks like a distorted half ellipse, ~160 nm in width and ~76 nm in height.

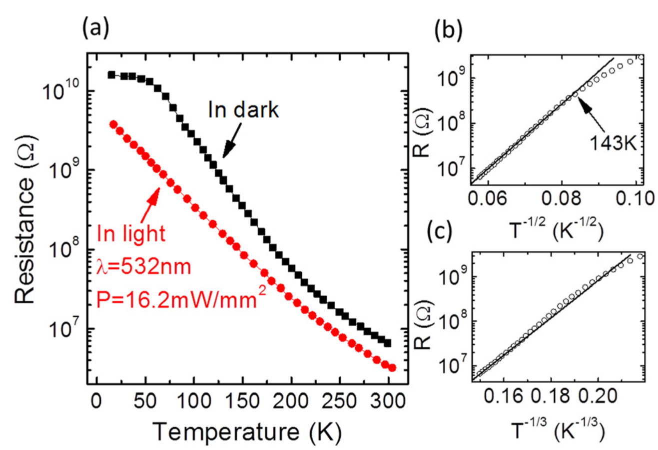


FIG. 2. (a) Resistance of the LAO nanowire grown on STO as a function of temperature, measured through the four SRO electrodes underneath LAO. Visibly light depresses the resistance by a factor up to 8. (b) Transport behavior in the form of one-dimensional variable-range hopping. (c) Transport behavior in the form of two-dimensional variable-range hopping. Combined with the results in (c) and (b) gives a better description to the transport behavior. Solid lines are guides for the eye.

(Fig. 2(c)). This result confirms that the conducting strip is indeed one-dimensional in nature.

The VRH form conduction indicates the occurrence of strong electron localization. There are two reasons for this. At first, the carrier density in the present q1DEG may be below the threshold value for metallic transport. Second, the effect of random scattering from lattice defects, such as oxygen vacancies, has been significantly enhanced by reduced dimensionality.

The q1DEG is further found to be susceptible for photo illumination, exhibiting reduced resistance when exposed to visible light. In a light of 16.2 mW/mm^2 (wavelength $\lambda = 532$ nm), for example, the resistance is depressed by a factor of ~8 at 50 K and ~1.9 at 300 K (Fig. 2(a)), though it remains semiconducting. This is a phenomenon similar to that observed in the q2DEG at the LAO/STO interface. Tentatively, we ascribe phenomenon to photo excitation which generates extra charge carriers thus improving the electronic transport of the q1DEG.

For the low dimensional electron systems, gating effect may be the most powerful approach tuning its transport properties. To get a quantitative description of the gating effect, in Fig. 3 we show the resistance as a function of gate biases. Without illumination, all of the resistance values fall onto a straight line as gate voltage varies, i.e., the resistance grows under negative V_Gs but reduces under positive V_Gs, a feature of the conventional gating effect. However, the gating effect is very weak. The relative resistance change $\Delta R/R = [R(V_G)-R(0)]/R(0)$ is, under a $|V_G|$ of 200 V, ~3.2% at $T = 150$ K and ~1.5% at $T = 300$ K. It may be ascribed to the conventional capacitive effect, appearing when the gate voltage is applied between the q1DEG and the back gate. In this case, the gating effect will be exclusively determined by the dielectric constant of STO. According to the literature, from

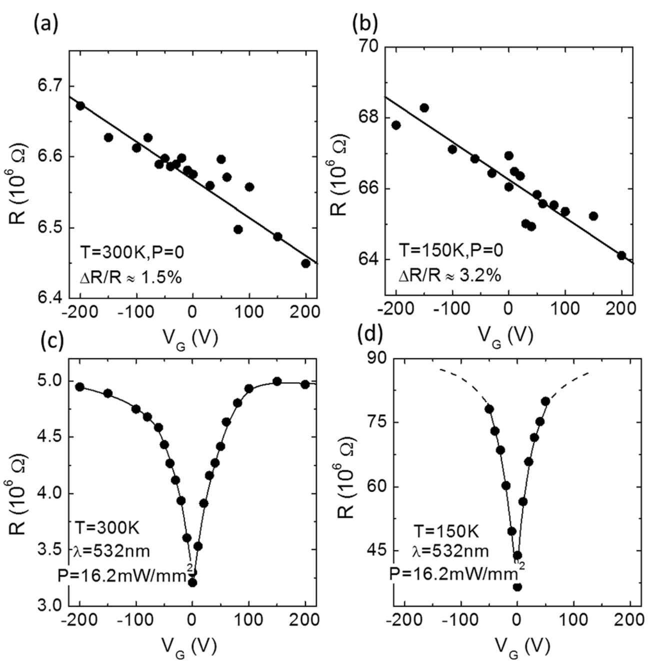


FIG. 3. (a) and (b) Resistances as functions of gate voltage, derived from the I–V curves recorded at 300 K (a) and 150 K (b). (c) and (d) Resistances as functions of gate voltage, derived from the I–V curves recorded in the presence of light at 300 K (c) and 150 K (d). Slight lines are guides for the eye.

150 K to 300 K, the dielectric constant of STO is reduced from 690 to 300.[20] Therefore $\Delta R/R$ is nearly halved.

Strong gating effect appears in the presence of photo excitation. As shown in Fig. 2(a), photo excitation causes an obvious resistance decrease. However, gate voltage produces a reverse effect to photo excitation. The gating effect is the strongest when gate bias begins to increase from 0 to 100 V, and tends to saturation above the gate biases of 100 V. A simple calculation shows that the line resistance of the q1DEG grows from $3.2 \times 10^6 \Omega$ for $V_G = 0$ to $4.9 \times 10^6 \Omega$ for $|V_G| = 200$ V, increased by ~53%. This combined effect is further enhanced at low temperatures. It is ~65% at 200 K and 114% at 150 K, the latter is obtained under a $|V_G|$ of 50 V. We failed to get the data above 50 V because of the electric breakdown of STO. However, we believe that the resistance change will be far more than this because of the absence of the tendency to saturation up to the bias of 50 V. These results imply that the efficiency for gate field to tune interfacial carriers has been significantly amplified by photo excitation.

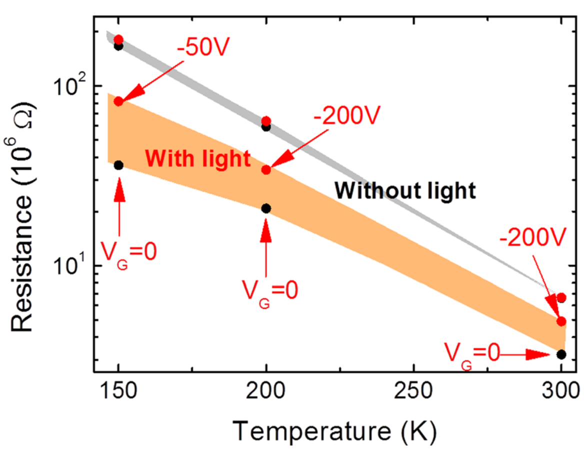
Basing on a simple analysis of photoelectric response (supplementary material, Figure S1), we can obtain a rough estimation for the carrier density of our q1DEG. For a LAO/STO q2DEG with carrier density of $7 \times 10^{12}\,cm^{-2}$ (supplementary material, Figures S2 and S3), it has been found that a light of 4.9 mW/mm^2 ($\lambda = 532$ nm) caused a conduction growth of ~8% (supplementary material, Figure S4). Ascribing this effect exclusively to the variation of carrier density, we found that the upper limit for photo carriers will be $\sim 8\% \times 7 \times 10^{12}\,cm^{-2} \approx 0.56 \times 10^{12}\,cm^{-2}$ for a light of 4.9 mW/mm^2, or, $\sim 1.9 \times 10^{12}\,cm^{-2}$ for a light of 16.2 mW/mm^2. Since the conduction of the q1DEG is nearly doubled in the light of 16.2 mW/mm^2 at the ambient temperature (Fig. 2(a)), the initial carrier density of the q1DEG should be comparable to the density of photo carriers, i.e., close to $1.9 \times 10^{12}\,cm^{-2}$. This density is much lower than that of the ordinary q2DEG (~ 2–$6 \times 10^{13}\,cm^{-2}$). It could be a general feature of the nanowire interfaces fabricated by the technique of sol-gel plus post annealing.

Since the relative resistance change is ~1.5% at 300 K, the tuned carrier density by a gate bias of −200 V is at most $\sim 1.5\% \times 1.9 \times 10^{12} \approx 2.9 \times 10^{10}\,cm^{-2}$. Aided by light illumination, however, a similar gate bias can result in a resistance growth of ~53%. In this case, we have to assume that the tuned carrier density could be well beyond $2.9 \times 10^{10}\,cm^{-2}$ to explain the experimental results or else we will obtain an unreasonable conclusion that the mobility of the remaining charge carriers is reduced by ~53% when only a few percent carriers are depleted by gate field.

In fact, the effects of light illumination and gating field have been separately studied for the 2DEG system at the LAO/STO interface.[21–25] It was found that photo excitation always improved electronic transport whereas gating voltage will either enhance or depress sheet resistance, depending on polarity. We noticed that in most of these works, gating field and illuminating light were scarcely applied simultaneously. This makes their combined effect remain undiscovered. Recently, Lei *et al.*[15] and Li *et al.*[26] reported that, with the help of photo illumination, gating field can cause a lattice polarization of STO, producing an extra tuning to the sheet carriers that is well beyond the conventional capacitive effect for the q2DEG. In principle, the gate-field-induced lattice polarization can also occur for the q1DEG though the electric field in STO may be inhomogeneous, resulting in enhanced gating effect. In this picture, we can understand the enhanced gating effect when illumination exists.

An unexpected phenomenon is the anomalous gating effect under positive biases. Aided by illumination, as shown in Fig. 3, positive bias enhances, rather than depresses, interface resistance. Take the result of 300 K as an example. Corresponding to the increase of gate bias from 0 to 150 V, the resistance grows from $\sim 3.2 \times 10^6 \Omega$ to $\sim 5.0 \times 10^6 \Omega$, enhanced by ~56%. This phenomenon is observed at all temperatures investigated, therefore is a general feature of the gating effect for our q1DEG. To interpret this phenomenon, we have to assume a depletion of charge carriers by positive biases. However, the gating effect is ordinary without illumination. Therefore, this abnormal effect must be associated with photo carriers. In general, photo carrier density is jointly determined by the excitation and re-combination rates, and a stable state will be seen when these two processes reach a dynamic equilibrium. In general, the energy barrier at the LAO/STO interface will prevent the re-combination of the excited electrons and holes, supporting a high photo carrier density. When a positive bias is applied, the interfacial potential will be depressed. This in turn leads to a reduction in photo carrier density. When this effect counteracts that generated by the gate bias-induced density increase, a decrease in interface conduction appears. This effect is expected to occur when the potential well at the interface is shallow so that it can be easily flattened by applied gate biases.

Fig. 4 is a summary of the combined effects of gate field and light, obtained with a laser power of 16.2 mW/mm^2 ($\lambda = 532$ nm), here only the data obtained under the V_G of 0 and -200 V ($|V_G| = 50$ V for $T = 150$ K in light) are shown; the results under positive gates are similar. At first glance, gate voltage simply counteracts the effect of light illumination, driving the q1DEG towards its initial high resistance state. However, this counteraction is incomplete, and the resistance remains lower than its initial value even under a gate voltage of -200 V. This is in sharp contrast to the case of 2DEG, for which the gate field is much more efficient, depleting more than photo carriers.



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In summary, one-dimensional electron gas at the LAO/STO interface has been prepared by the technique of electrostatic spinning plus post annealing. An electronic transport behavior with the character of one-dimensional variable-range hopping has been detected. Strong effect of visible light illumination on the transport process is observed, which depresses the resistance of the nanowire by a factor up to 8. More interestingly, the gating effect is amplified by photo excitation by 35-fold, which indicates an extra carrier tuning, and the resistance grows under not only negative back gates but also positive gates, different from the normal gating effect without illumination. In addition to presenting a feasible technique for the preparation of q1DEG, this work reveals the distinct characteristics of the q1DEG which deserves further studies.

See supplementary material for further photo-electronic behaviors of the 1DEG and the transport behaviors of the 2DEGs at the amorphous-$LaAlO_3$/$SrTiO_3$ interface.

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