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The substrate thickness dependence of the photovoltage in $LaAlO_{3-\delta}$/Si heterostructures

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The photoelectric properties of $LaAlO_{3-\delta}$/Si heterostructures with different substrate thicknesses were systematically investigated, in which the $LaAlO_{3-\delta}$ thin films were epitaxially grown on *p*-type Si substrates by a computer-controlled laser molecular-beam epitaxy system. Picosecond photoelectric response was observed, and the photoelectric sensitivity was improved greatly by decreasing the thickness of the Si substrates. The maximum photoelectric sensitivity reached 85.6 V/W, and faster photoelectric response was obtained with thinner Si substrate. The experimental results demonstrate that the photoelectrical effects on heterostructures consisting of perovskite oxide and thin silicon substrate are not only with fast response but also with high sensitivity.
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Much of the recent scientific interest in developing oxides has been devoted to engineering them for novel functionality.[1] The heterostructures of perovskite oxides have generated considerable research activities due to the intrinsic properties of perovskite oxides and the interface effects.[2–6] The $LaAlO_3$ is one of the perovskite oxide materials and itself is an insulator with a band gap of ~5.6 eV. The $LaAlO_3$ single crystal wafers have been widely used as the substrates for growing perovskite oxide thin films, especially for superconductors. The $LaAlO_3$ has also attracted much attention as one of the most promising alternative gate dielectrics due to its advantages such as high dielectric constant, wide gap, and chemical and compositional stability. We have reported the characteristics of amorphous $LaAlO_3$ thin films grown on Si substrates[7] and the heteroepitaxial growth of $LaAlO_3$ films on Si substrates.[8] In previous work, we studied the photovoltaic characteristics of $BaTiO_{3-\delta}$ (BTO)/Si heterostructures and found that the physical properties of BTO/Si heterostructures varied greatly by changing the oxygen content of the BTO thin films.[9] In this letter, we report a systematic study on the substrate thickness dependence of photovoltage in $LaAlO_{3-\delta}$ (LAO)/Si heterostructures. We not only observed the fast-response photoelectric effect in LAO/Si heterostructures but also found that the photoelectric sensitivity was improved greatly by decreasing the thickness of Si substrates.

The LAO thin films were epitaxially grown on *p*-type Si substrates with a resistivity of 12.95 Ω cm by a computer-controlled laser molecular-beam epitaxy system. As mentioned in our previous report,[9,10] in order to prevent the formation of a SiO_2 interfacial layer, we used the two-step method to epitaxially grow the LAO thin films on Si substrates. At first, about two-unit-cell thick LAO film was deposited on the Si substrate at room temperature; then the substrate temperature was raised to 600 °C. The growth process was monitored by *in situ* reflection high-energy electron diffraction (RHEED). When the RHEED streak pattern appeared, LAO thin film with a thickness of 400 nm was continuously deposited with a repetition rate of 4 Hz and a laser energy density of 2 J/cm^2. As we observed in BTO/Si heterostructures, more oxygen vacancies in BTO film could result in higher sensitivity of photoelectric response in BTO/Si heterostructures. In order to get a high sensitivity, an oxygen pressure of 1×10^{-4} Pa was maintained during the LAO film deposition.

Figure 1 shows the x-ray diffraction (XRD) θ-2θ scan curve of the LAO/Si heterostructure. Except for the diffraction peaks of LAO (001) and (002) and Si (002) and (004), there are no diffraction peaks from impurity phases or randomly oriented grains, which indicates that the LAO film is a single phase and *c*-axis oriented. The Hall coefficient measurement confirmed that the LAO film is electron conductive, and the resistivity is 6.4×10^{-3} Ω cm at room temperature.

The photoelectric properties were investigated under the illuminations of pulsed lasers with the wavelength of 355 and 308 nm, as well as a continuous HeNe laser of 632.8 nm. The size of our LAO/Si sample was 30×30 mm^2; in order to study the influence of substrate thickness on the photoelectric effect, we chose a LAO/Si of 10×10 mm^2 and cut the sample into four pieces with equal areas. The thickness of Si substrates was 0.71 mm. We polished three pieces of Si

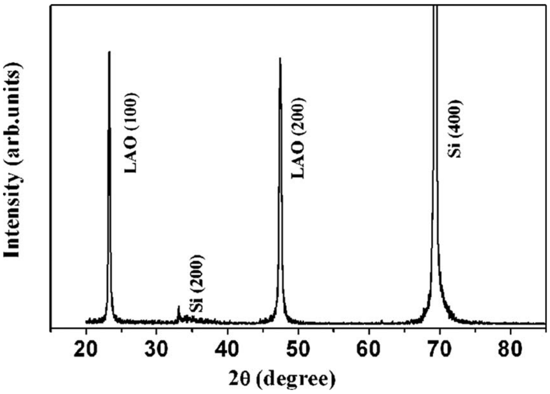

FIG. 1. The XRD pattern of LAO thin film with a thickness of 400 nm grown on *p*-type Si substrate.

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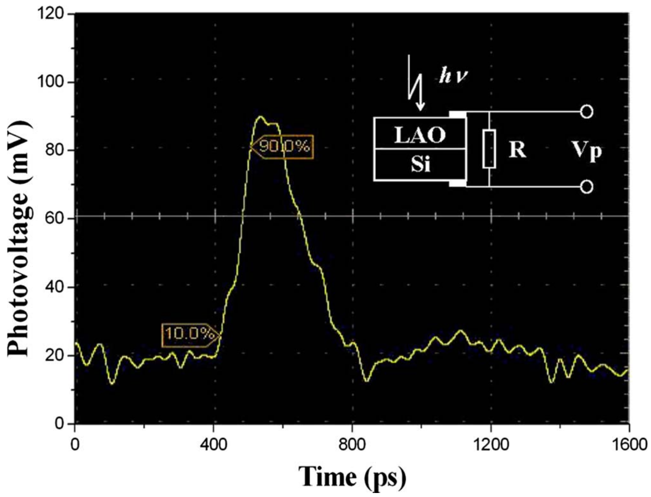

FIG. 2. (Color online) A typical photovoltaic pulse of LAO/Si heterostructure under the excitation of a 355 nm pulsed laser with 25 ps duration. The inset shows the schematic circuit of the measurement.

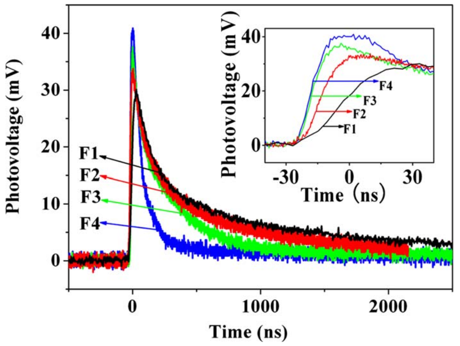

FIG. 3. (Color online) The photovoltaic responses of LAO/Si heterostructures under the illumination of XeCl pulsed laser for samples F1, F2, F3, and F4. The inset is the rise time of photovoltaic response.

substrates mechanically and let the thicknesses decrease to 0.44, 0.19, and 0.10 mm, respectively. In the following description, the four samples with equal size of 5 × 5 mm^2 and various substrate thicknesses will be denoted as F1 (0.71 mm), F2 (0.44 mm), F3 (0.19 mm), and F4 (0.10 mm), respectively. For the photovoltaic measurements, two indium electrodes were painted on the surfaces of LAO film and Si substrate, as shown in the insets of Figs. 2 and 4. During the measurements, the electrodes were always kept in the dark to prevent the generation of any electrical contact photovoltage. All of the photoelectric measurements were carried out at room temperature.

Figure 2 displays a typical photovoltaic response of LAO/Si heterostructure illuminated by a 355 nm pulsed laser with 25 ps duration. The waveform was recorded by an oscilloscope with 20 GHz bandwidth. In order to reduce the influences of the measuring system and the capacitance of the *p*-*n* heterojunction, we used a LAO/Si of 3 × 2 mm^2 with 0.1 mm Si substrate. A 0.1 Ω resistance was connected in parallel with the LAO/Si heterojunction to study the photovoltaic response. The 10%–90% rise time is 86 ps, and the full width at half maximum (FWHM) is 178 ps for the photovoltaic response. The photovoltaic response is faster than that we observed in $\mathrm{La_{0.7}Sr_{0.3}MnO_3/Si}$ and $\mathrm{SrTiO_{3-\delta}/Si}$ heterostructures.[10] It is noteworthy that all of our experimental results proved that similar to that in the traditional semiconductor *p*-*n* junction, the photoelectrical process is in a picosecond order in the *p*-*n* heterostructures consisting of complex oxide and Si.

The influence of substrate thickness on photoelectrical effects of LAO/Si heterostructure was systematically investigated on samples F1, F2, F3, and F4 by a 632.8 nm continuous HeNe laser (power: 5 mW) and a 308 nm XeCl excimer pulsed laser (pulse width: 20 ns and energy density: 0.1 $\mathrm{J/cm^2}$) with a laser spot diameter of 2 mm.

Figure 3 shows the substrate thickness dependence of the photovoltaic response. The photovoltaic signals were measured by an oscilloscope with 500 MHz bandwidth and an input impedance of 50 Ω. For the four samples F4, F3, F2, and F1, the 10%–90% rise times were 13.3, 13.9, 21.4, and 38.3 ns, respectively, and the FWHMs were 79.2, 134.7, 180.6, and 258.2 ns, respectively, when the LAO film was illuminated with a XeCl pulsed laser. We note that the photoelectric signals for all four samples are composed of a fast rise time and a slow decay. The rise time of the photoelectric signal is faster for the heterostructure with thinner substrate. Meanwhile, the FWHM decreases with the decrease in substrate thickness. It can be understood in the following way: electrons and holes induced by laser were separated by built-in electric field at the interface of LAO and Si, and those holes reached the surface of the substrate faster for thinner substrate so that faster photoelectric response can be observed. Smaller FWHM for the heterostructure with thinner substrate can be understood in the similar way.

Figures 4(a) and 4(b) show the substrate thickness de-

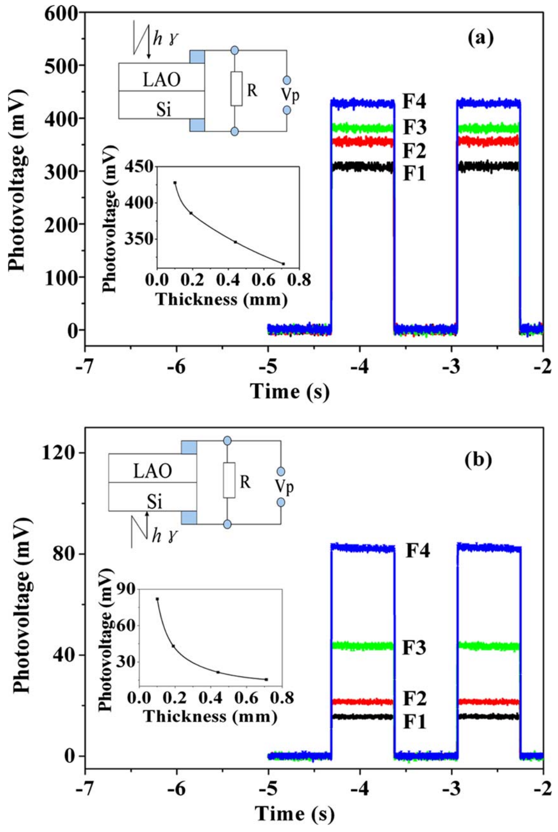

FIG. 4. (Color online) The photovoltages of samples F1, F2, F3, and F4 with a HeNe laser of 5 mW for irradiating the LAO/Si heterostructures through (a) the LAO film and (b) the Si substrate. The insets in figures (a) and (b) show the schematic circuits of the measurements and the Si substrate thickness dependence of the photovoltage, respectively.

pendence of the photovoltage. The photovoltages were recorded by the oscilloscope with 500 MHz bandwidth with an input impedance of 1 MΩ. The photovoltages for sample F1, F2, F3, and F4 were 316, 346, 386, and 428 mV, respectively, when the LAO film was illuminated by a 5 mW HeNe laser, and 16, 22, 45, and 82 mV, respectively, when the Si substrate was illuminated by HeNe laser. From Fig. 4, it can be clearly seen that (1) photoelectrical sensitivity is higher when the LAO film was illuminated than that when the Si substrate was illuminated and (2) the photovoltage in F4 is 1.35 times that in F1 when the LAO film was illuminated and 5.13 times that in F1 when the Si substrate was illuminated. The maximum photoelectric sensitivity of F4 was 85.6 V/W when the LAO film was illuminated.

As we all know, the *n*-type LAO grown onto *p*-type Si could form a *p*-*n* heterojunction. The electrons with higher density in *n*-type LAO film than those in Si should diffuse into Si, and the holes with higher density in Si than those in LAO should diffuse into LAO. The diffusion causes a built-in electric field in the space charge region around the interface. With the illumination of light, photoninduced carriers were separated by the built-in field at the interface and caused the photovoltage we measured. In the present case, the photon energy from the HeNe laser (~ 2 eV) is larger than the band gap energy of Si (~ 1.1 eV) and less than that of LAO (~ 5.6 eV). So the photons can pass through LAO film and create the photocarriers, electrons, and holes in Si when the LAO film was illuminated with HeNe laser. The absorption coefficient and absorption length of HeNe laser in Si are about 4×10^3 cm^{-1} and 2.5 μm,[11] respectively. The created photocarriers near the interface were separated by the built-in field and caused a photovoltage. However, when the Si substrate was illuminated with HeNe laser, the photons were absorbed directly and the photocarriers were created in Si surface. The created photocarriers in Si surface diffused to the interface, then were separated by the built-in field and caused a photovoltage, so the photoelectrical sensitivity is much lower than that in the case of illuminating the LAO film; meanwhile the recombination of some photocarriers should also occur during the diffusing process.

In summary, the fast response in picosecond and high sensitivity photoelectrical characteristics were observed in LAO/Si *p*-*n* heterojunctions. Experimental results show that the decrease in the substrate thickness is an effective method for improving the photovoltaic sensitivity in *p*-*n* heterojunctions. It suggests potential applications in optoelectronic detection.

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