Transient lateral photovoltaic effect in *p-n* heterojunctions of $La_{0.7}Sr_{0.3}MnO_3$ and Si

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A transient lateral photovoltaic effect (LPVE) has been observed in p-$La_{0.7}Sr_{0.3}MnO_3$/n-Si heterojunctions. Under the nonuniform irradiation of a pulsed laser, the LPVE shows high sensitivity to the spot position on the $La_{0.7}Sr_{0.3}MnO_3$ surface. A mechanism based on the well established model for the LPVE in conventional semiconductors has been applied to explain the LPVE in the heteroepitaxial junctions of perovskite-type metal oxides. The large LPVE in the heteroepitaxial junctions is expected to make the perovskite-type metal oxide a new and faster candidate for position-sensitive photodetectors. © *2006 American Institute of Physics*.
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Considerable attention has been paid to the development of heteroepitaxial junctions of perovskite-type metal oxides (ABO_3), which can be expected to exhibit novel characteristics and display a high sensitivity to external magnetic and electric fields.[1–6] Many studies have been carried out with regard to the photoelectric effect on perovskite-based *p-n* junctions.[7,8] In our previous work, we also reported nanosecond and picosecond photoelectric characteristics discovered in $La_{0.9}Sr_{0.1}MnO_3/SrNb_{0.01}Ti_{0.99}O_3$, $La_{0.7}Sr_{0.3}MnO_3$/Si, and $SrTiO_{3-\delta}$/Si heterostructures.[9] Whereas all these previous works focused on the photovoltaic effect across the *p-n* junction of oxides that were uniformly illuminated by a laser, almost no study has been reported for the lateral photovoltaic effect (LPVE) measured on the surface of the *oxide* heterojunctions. This LPVE on conventional semiconducting *p-n* junctions with nonuniform illumination was found 70 years ago[10] and has been applied for use in position-sensitive detectors for more than 40 years.[11] With nonuniform illumination on the *p-n* junction of *perovskite-type metal oxides*, a LPVE in addition to the transverse photovoltage has been expected. In this letter, we present the transient LPVE, which was measured on a $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) surface upon illumination by a pulsed laser spot on the LSMO surface of a LSMO/Si heterojunction.

A LSMO/Si *p-n* junction was fabricated by growing a *p*-type LSMO (400 nm) layer on an *n*-type Si (001) substrate, following the procedure we reported previously. The *in situ* reflection high-energy electron diffraction and *ex situ* x-ray diffraction showed that the LSMO film has a good crystallized structure and a smooth surface with *c*-axis orientation. The junction exhibits good rectifying current-voltage characteristics.[9] The Hall effect measurement showed that the carrier density of LSMO is around 3×10^{18} cm^{-2}, much greater than that of *n*-type Si (around 1×10^{16} cm^{-2}); therefore, the depletion region in Si should be much thicker than that of LSMO. The schematic for the LPVE measurement is shown in the inset of Fig. 1. A small area of 0.3 mm diam is irradiated on the LSMO surface by a 308 nm XeCl excimer laser beam (pulse width 20 ns, energy density 0.6 mJ mm^{-2}). The LPVE between the indium electrodes B ($x=3$ mm, $y=0$) and A ($x=-3$ mm, $y=0$), V_{BA} defined as V_B-V_A, is measured and recorded by a 500 MHz sampling oscilloscope terminated into 1 MΩ at ambient temperature. The electrodes are always kept in the dark to prevent the generation of any electrical contact photovoltage. In addition, a steady open-circuit photovoltage, ~5 mV, was also observed when this heterojunction was illuminated by a constant He–Ne laser (power density 0.5 mW mm^{-2}), and this phenomena is undergoing. We focus on the transient LPVE.

As displayed in Fig. 1, the transient LPVE to the laser pulse depends on the position of the spot in the x axis and undergoes a sign reversal as the laser spot travels from one electrode to the other. The changeover in sign occurs halfway between the two electrodes (with $x=0$).

The maximum LPVE values, V_{BA}^m, are plotted in Fig. 2 as a function of the laser spot position (x,y) on the LSMO surface. In the region between the contacts, V_{BA}^m varies quite linearly with x for different y values. The open-circuit sensitivity, which means the variation of the output voltage in

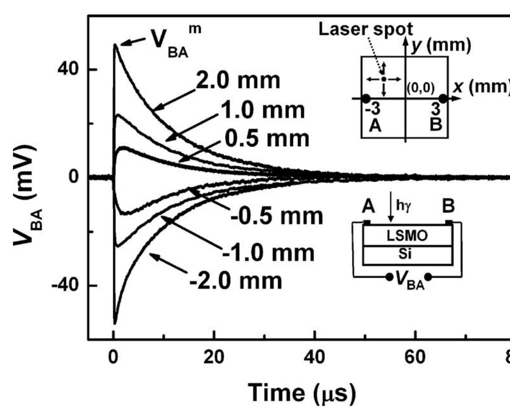

FIG. 1. Transient lateral open-circuit photovoltages after excitation with a 308 nm laser pulse on the LSMO/Si *p-n* junction in the x direction at $y=0$. Numbers in the figure denote the x coordinate values of the laser spot positions. The top inset shows the layout of the sample with contacts A (−3 mm, 0), B (3 mm, 0), and the laser spot (x,y). The bottom one displays the schematic circuit of the V_{BA} measurement.

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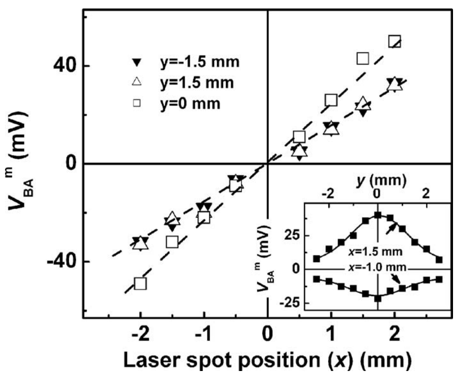

FIG. 2. Dependence of the peak photovoltage V_{BA}^{m} on the position of the laser spot in the x direction and y direction (the inset).

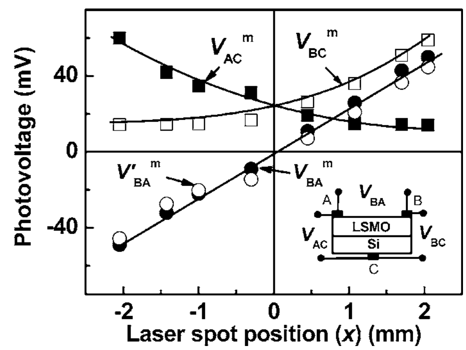

FIG. 4. Lateral peak photovoltage V_{BA}^{m} (solid circle point), and transverse peak photovoltages V_{AC}^{m} (solid square point) and V_{BC}^{m} (open square point), as a function of the position of the laser spot in the x direction at $y=0$. The open circle points are a simple addition of transverse photovoltages, $V'^{m}_{BA}=V_{BC}^{m}-V_{AC}^{m}$. The lines are guides for the eye. The inset displays the schematic electrode setting for the V_{BA}, V_{BC} and V_{AC} measurements.

V mJ^{-1} for a 1 mm displacement of the spot, is about 0.59 (0.39) V mJ^{-1} mm^{-1} for $y=0$ (± 1.5) mm, respectively. The response to the irradiation position in the y direction is shown in the inset of Fig. 2.

Figure 3 summarizes the spatial distribution of the peak values of LPVE in the plane of the junction. The voltage sign reversal is obtained if the spot is moved across the center between the two contacts. The signal is symmetric on the reflection in a plane normal to the y axis at $y=0$.

An indium electrode C was fixed at the center of the Si side ($x=0,y=0$) to obtain the dependence of the transverse photovoltage (TPV) on the position of the laser spot. Figure 4 shows the peak TPVs, V_{BC}^{m} and V_{AC}^{m}, as functions of positions (x) of the laser spot on the LSMO surface with $y=0$. It is clear that the positive TPV, V_{BC} or V_{AC}, also depends on the position of the laser spot or contacts and shows a higher value with the laser spot being closer to B or A. The position dependence of TPV suggests that the setup of the electrodes in a p-n junction is very important for a photon detector application. From the experimental data, we can find that the peak values of TPV (V_{BC}^{m} and V_{AC}^{m}) and the peak values of LPVE (V_{BA}^{m}) follow a simple relation, $V_{BA}^{m}=V'^{m}_{BA}=V_{BC}^{m}-V_{AC}^{m}$. In Fig. 4, V'^{m}_{BA} is denoted by open dots.

To understand the mechanism causing the LPVE in the p-n junction of LSMO/Si, Fig. 5 shows the schematic energy band profile and the transient movement of photon-generated carriers for the p-LSMO/n-Si heterojunction. The 308 nm photon energy of the laser pulse is above the band gap of LSMO (≈ 1.0 eV) and Si (≈ 1.12 eV), so that electron-hole pairs are generated in the LSMO layer and the Si substrate. The photogenerated carriers are swept across the junction, and the electrons created with the higher potential in the LSMO side move to the n side of Si, and the holes in the Si side move to the p side of the LSMO. Because the structure is only partially illuminated by laser pulse, the carrier concentration is much greater in the illuminated zone, generating a gradient between the illuminated and the nonilluminated zones. So the excess holes in the LSMO layer and the excess electrons in the Si layer (majority carriers) move radially away from the illuminated spot in the lateral (in plane) direction. If the lateral distance of the center of mass of the carrier packet from each probe is different, then the quantity and time evolution of the collected carriers on the two probes are different. A transient lateral field is therefore set up, as well as the LPVE. With time evolution, the nonequilibrium carriers redistribute themselves accomplishing charge neutralization, which is corresponding to the decay with time of the LPVE after reaching the maximum of the signal shown as Fig. 1. It has been known that the temperature gradient at the position of the laser spot in the transverse direction (perpendicular to the film surface) can cause a LPVE in an anisotropy system,[12] which is called the thermoelectric effect or Seebeck effect. However, in the device studied in this letter, the substrate is untilted, in other words, it is c-axis oriented. So in the surface plane the system is isotropic, and the thermoelectric effect should be ruled out in the measured voltage. When the light spot is at the center between A and B on the p-LSMO, the lateral photovoltage V_{BA} is zero due to the diffusion symmetry. If the light position x is positive (negative), V_{BA} is positive (negative) because the generated excess holes are closer to B (A). Furthermore, the signal becomes

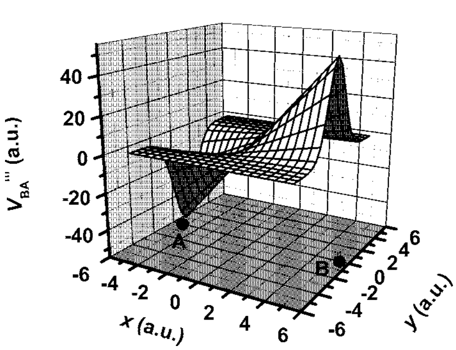

FIG. 3. Three-dimensional plot for the V_{BA}^{m} as a function of the position of the laser spot.

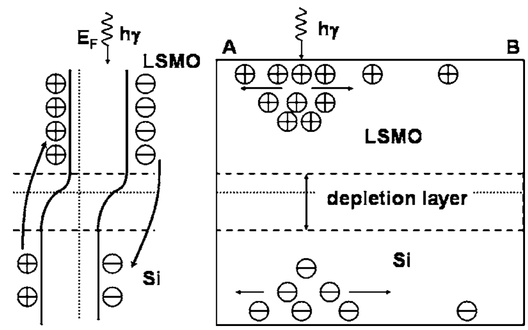

FIG. 5. Schematic band structure for the LSMO/Si junction, and the schematic movement of the photon created carriers for the system irradiated by the laser spot.

stronger when the light spot is closer to B or A. When $y \neq 0$, the V_{BA}^{m} is smaller than that of $y=0$ at the fixed x as shown in the inset of Fig. 2. This can be easily understood for the reason that the distance from the light spot to the A or B with $y \neq 0$ is larger than that with $y=0$.

In conclusion, the p-LSMO/n-Si heterojunction has been found to exhibit a large and fast LPVE, and the peak photovoltage shows a high sensitivity of laser spot position between the contacts on the LSMO surface. Under laser irradiation, electron-hole pairs are generated and flow in agreement with a gradient between the irradiated and unirradiated regions due to the nonuniformity of the irradiation. When equilibrium has been attained, the lateral diffusion process is counterbalanced by the appearance of a lateral component of the electric field vector in addition to the usual transverse component. The large LPVE in the heteroepitaxial junctions is expected to make the perovskite-type metal oxide a new and faster candidate for position-sensitive photodetectors.

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[1] S. Jin, T. H. Tiefel, M. McCormack, R. A. Fastnacht, R. Ramesh, and L. H. Chen, Science **264**, 413 (1994).
[2] A. Asamitsu, Y. Tomioka, H. Kuwahara, and Y. Tokura, Nature (London) **388**, 50 (1997).
[3] M. Fiebig, K. Miyano, Y. Tomioka, and Y. Tokura, Science **280**, 1925 (1998).
[4] C. Mitra, P. Raychaudhuri, G. Kobernik, K. Dorr, K.-H. Muller, L. Schultz, and R. Pinto, Appl. Phys. Lett. **79**, 2408 (2001).
[5] H. Tanaka, J. Zhang, and T. Kawai, Phys. Rev. Lett. **88**, 027204 (2002); J. Zhang, H. Tanaka, and T. Kawai, Appl. Phys. Lett. **80**, 4378 (2002).
[6] K.-J. Jin, H. B. Lu, Q. L. Zhou, K. Zhao, B. L. Cheng, Z. H. Chen, Y. L. Zhou, and G. Z. Yang, Phys. Rev. B **71**, 184428 (2005); H. B. Lu, S. Y. Dai, Z. H. Chen, Y. L. Zhou, B. L. Cheng, K.-J. Jin, L. F. Liu, G. Z. Yang, and X. L. Ma, Appl. Phys. Lett. **85**, 032502 (2005); H. B. Lu, G. Z. Yang, Z. H. Chen, S. Y. Dai, Y. L. Zhou, K.-J. Jin, B. L. Cheng, M. He, L. F. Liu, H. Z. Guo, Y. Y. Fei, W. F. Xiang, and L. Yan, *ibid.* **84**, 5007 (2004).
[7] T. Muramatsu, Y. Muraoka, and Z. Hiroi, Solid State Commun. **132**, 351 (2004).
[8] J. R. Sun, C. H. Lai, and H. K. Wong, Appl. Phys. Lett. **85**, 37 (2004); J. R. Sun, B. G. Shen, Z. G. Sheng, and Y. P. Sun, *ibid.* **85**, 3375 (2004).
[9] H. B. Lu, K.-J. Jin, Y. H. Huang, M. He, K. Zhao, B. L. Cheng, Z. H. Chen, Y. L. Zhou, S. Y. Dai, and G. Z. Yang, Appl. Phys. Lett. **86**, 241915 (2005); K. Zhao, Y. H. Huang, Q. L. Zhou, K.-J. Jin, H. B. Lu, M. He, B. L. Cheng, Y. L. Zhou, Z. H. Chen, and G. Z. Yang, *ibid.* **86**, 221917 (2005); Y. H. Huang, H. B. Lu, M. He, K. Zhao, Z. H. Chen, B. L. Cheng, Y. L. Zhou, K.-J. Jin, S. Y. Dai, and G. Z. Yang, Sci. China, Ser. G **48**, 381 (2005).
[10] W. Schottky, Phys. Z. **31**, 913 (1930).
[11] J. T. Wallmark, Proc. IRE **45**, 474 (1957).
[12] K. Zhao, K.-J. Jin, Y. H. Huang, H. B. Lu, M. He, Z. H. Chen, Y. L. Zhou, and G. Z. Yang, Physica B **373**, 72 (2006).