Change in photovoltage due to an external magnetic field in a manganite-based heterojunction

Z. G. Sheng, B. C. Zhao, W. H. Song, and Y. P. Sun[a)]
Key Laboratory of Materials Physics, Institute of Solid State Physics, Chinese Academy of Sciences, Hefei 230036, China

J. R. Sun and B. G. Shen
State Key Laboratory for Magnetism, Institute of Physics and Centre for Condensed Matter Physics, Chinese Academy of Sciences, Beijing 100080, China

(Received 10 January 2005; accepted 14 October 2005; published online 5 December 2005)

The effect of magnetic field on the photovoltaic effect (PVE) has been investigated for a manganite-based heterojunction composed of a $La_{0.7}Ce_{0.3}MnO_3$ film and a 0.5 wt % Nb-doped $SrTiO_3$ substrate. A linear decrease in the photovoltage (V_{oc}) with magnetic fields is observed and the relative variation of V_{oc} [defined as $1-V_{oc}(H)/V_{oc}(0)$] is larger than 10% under a field of 0.5 T at a temperature $T=16.5$ K. There is a proportional relation between ΔV_{oc} and the magnetoresistance of the heterojunction. We attribute the modulation of PVE to variation of magnetization and resistance of depletion layer by external magnetic fields. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2140878]

Recently, intensive research activities have been focussed on the fabrication of heterojunction using manganites for their rich physical properties.[1] It has been found that fabricated heterojunctions can have an excellent rectifying property through properly controlling dopant species and the doping level of the oxides.[2,3] Compared with conventional semiconductors, the manganites have unique features, such as a strongly correlated electronic state and a magnetic state dependent band structure.[4] Hence, one may anticipate that the properties of manganite-based heterojunctions can be tuned mangnetically, which is of special interest from the applications viewpoint. Recently, our experimental results have shown that manganite-based heterojunctions are magnetically tunable, i.e., the diffusion/breakdown voltage and the junction resistance undergo a great change under the action of external magnetic fields.[5]

More recently, we reported the photovoltaic effect (PVE) in a manganite-based heterojunction.[6,7] Although the PVE mechanism is not very clear at present, it is apparent that the PVE is related to the magnetic behaviors of manganite films in the heterojunction. We know that the magnetic behavior of manganite films can be changed by external magnetic fields. So, it should be of significance to test whether the observed PVE can be manipulated by the external magnetic field. In this letter, we perform comprehensive studies on the effect of external magnetic field on the PVE in a $La_{0.7}Ce_{0.3}MnO_3-SrTiO_3-Nb$ (LCEM/STON) heterojunction.

The LCEM/STON heterojunction was fabricated by growing a (110) oriented LCEM film (~500 Å in thickness) on 3×5 mm^2 STON single crystal substrate with the (001) orientation using laser ablation. The resistance was measured using the standard four-probe technique in the temperature range of 10–300 K using a closed-cycle He refrigerator with optical windows. For the PVE measurement, the sample was mounted in a vacuum which was sealed by a double quartz glass window, a He–Ne laser of the wavelength $\lambda=632.8$ nm, and the power density of 1 mW/mm^2 was used to illuminate on LCEM film surface perpendicularly through the window. Simultaneously, the external magnetic fields in the range of 0–1 T are supplied by a magnet. A schematic illustration for the experiment setup is shown in Fig. 1. The current-voltage (*I-V*) characteristics and magnetization of the heterojunction were measured on commercial PPMS and SQUID (MPMS) magnetometer, respectively.

Figure 1 is the response of open-circuit photovoltage (V_{oc}) to light illumination measured at $T=50$ K (light power density $P=0.34$ mW/mm^2). It shows that the sample exhibits an obvious PVE, and the V_{oc} shows a quick switch between ~0 and ~2.0 mV corresponding to "light on" and "light off" similar to the results previously reported.[7] The temperature dependence of the V_{oc} for a fixed laser power density of $P=0.34$ mW/mm^2 is shown in Fig. 2. It reveals a nonlinear increase of V_{oc} as the temperature decreases, and a local maximum appear near 150 K.

To test whether the observed PVE in the LCEM/STON heterojunction can be influenced by applied magnetic fields,

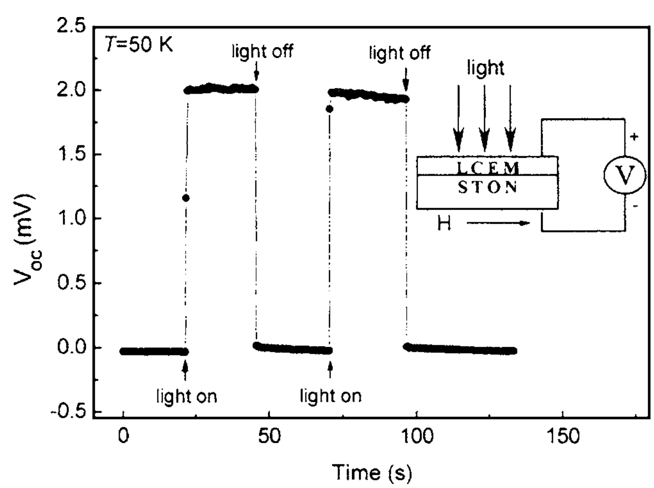

FIG. 1. Response of photovoltage to light illumination measured at a constant temperature of 50 K under the light power density of 0.34 mW/mm^2 ($\lambda=632.8$ nm). Inset is a schematic illustration of the PVE measurement under magnetic fields.

a)Electronic mail: ypsun@issp.ac.cn

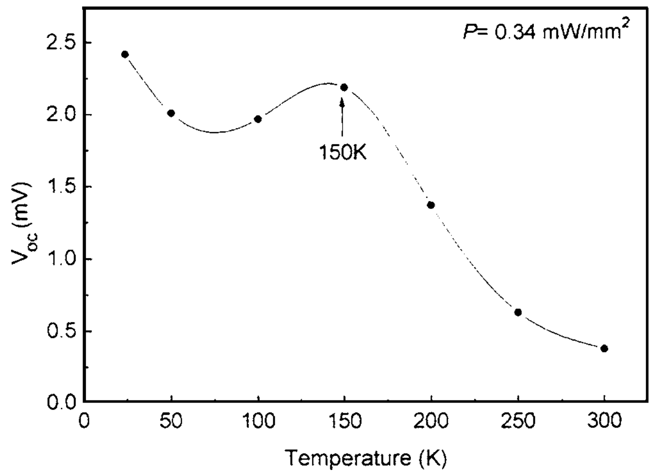

FIG. 2. Temperature dependence of photovoltage V_{oc} under the light power density of 0.34 mW/mm^2.

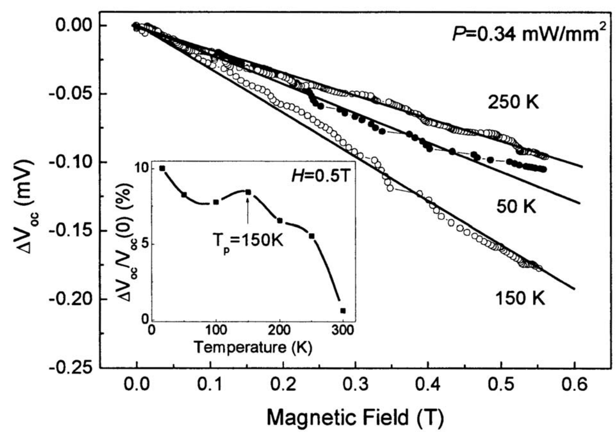

FIG. 4. Variation of photovoltage ΔV_{oc} as function of magnetic field at selected temperatures 50, 150, and 250 K. The inset plot shows the temperature dependence of relative variation of photovoltage $\Delta V_{oc}/V_{oc}(0) \times 100\%$. The used light power density is 0.34 mW/mm^2.

we apply an external magnetic filed of 0.5 T on the heterojunction. The results are shown in Fig. 3. Without magnetic fields, V_{oc} stays at a stable value under the constant light illumination. However, as an external magnetic fields of 0.5 T parallel to the film surface is applied, V_{oc} shows a quick decrease, and its relative variation $[$defined as $1 - V_{oc}(H)/V_{oc}(0)]$ is larger than 10% at T=16.5 K. Moreover, V_{oc} can return to the previous value if the external field is removed, that is, the dependence of the V_{oc} on the magnetic fields is reversible. Similar phenomenon has been observed in the whole measured temperature range. In order to investigate the effect of the external magnetic fields on the PVE further, we applied an external magnetic fields to the film before light illumination, Fig. 3 shows that the magnitude of V_{oc} also keeps ~10% below the V_{oc} value without external filed. These results reveal unambiguously that the external magnetic fields can manipulate the PVE of a LCEM/STON heterojunction. A similar phenomenon was also been observed in other manganite-based heterojunctions, such as $La_{0.32}Pr_{0.35}Ca_{0.33}MnO_3$/STON (not shown), which indicates that the magnetically tunable PVE is a common feature of the manganite-based heterojunctions.

We also measure V_{oc} by varying the external fields for constant temperature and light power density. Figure 4 shows the variation of photovoltage (ΔV_{oc}) with magnetic fields for selected temperatures 50 K, 150 K, and 250 K. ΔV_{oc} decreases monotonously with applied fields, and the field dependence of $V_{oc}(H)$ can be described as following equation:

$$V_{oc}(H) = V_{oc}(0) = \alpha(T)H, \tag{1}$$

where $V_{oc}(H)$ and $V_{oc}(0)$ represent the photovoltage with and without magnetic fields, respectively, H is magnetic fields intensity, and $\alpha(T)$ is a temperature dependent parameter. For a constant magnetic field of 0.5 T, the temperature dependence of $\Delta V_{oc}/V_{oc}(0)$ is plotted in inset of Fig. 4 in the temperature range of 20–300 K. It shows that $\Delta V_{oc}/V_{oc}(0)$ does not change monotonically with temperature and $\Delta V_{oc}/V_{oc}(0)$ has a bump near 150 K. It is interesting that $\Delta V_{oc}/V_{oc}(0)$ and $V_{oc}(T)$ curves show a similar temperature-dependent feature (Figs. 2 and 4). In other words, both of them have a bump around 150 K. The magnetization of LCEM/STON heterojunction under external magnetic fields of 0.001 T and 0.5 T was measured in the temperature range of 5–300 K. However, it is difficult to find some unambiguous relation between ΔV_{oc} and ΔM (not shown here).

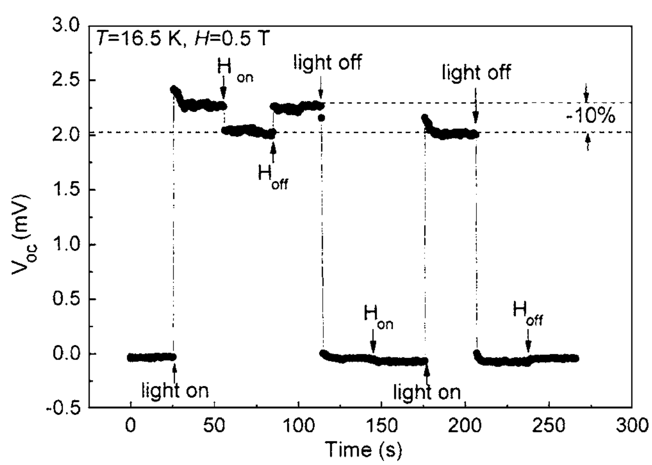

FIG. 3. Response of photovoltage to light illumination measured at a constant temperature of 16.5 K with the light power density of 0.34 mW/mm^2 and at an applied magnetic field of 0.5 T parallel to the film surface of LCEM/STON.

As for the origin of the magnetic dependence of V_{oc} observed in a LCEM/STON heterojunction, it may be a result of the variation of the built-in electric field in the depletion layer under magnetic fields. In order to test whether this assumption is true, we performed the measurement of the resistance of the heterojunction (R_j) since built-in field can be reflected by R_j. The zero-bias junction resistance at zero magnetic field $R_j(0)$ and at an external magnetic field $R_j(H)$ were obtained through measuring their I-V curves and calculating I-V curves according to $R_j = \partial V/\partial I$ for $I=0$. The temperature dependence of magnetoresistance (MR) of the heterojunction, defined as $MR(j) = [(R_j(H) - R_j(0))/R_j(0)]$, is shown in Fig. 5(a). MR exhibits a negative signal in the whole measured temperature range with two local maximums located at T_{p1}=274 K and T_{p2}=150 K, respectively. Considering that the structure of the heterojunction is composed of LCEM film and the depletion layer and the substrate, the resistance of the heterojunction can be expressed as $R_j = R_f + R_d + R_s$, where R_j, R_f, R_d, and R_s are the resistance of the heterojunction, the LCEM film, the depletion layer, and the substrate, respectively. Noting that the behavior of STON is magnetic field independent, we attribute the

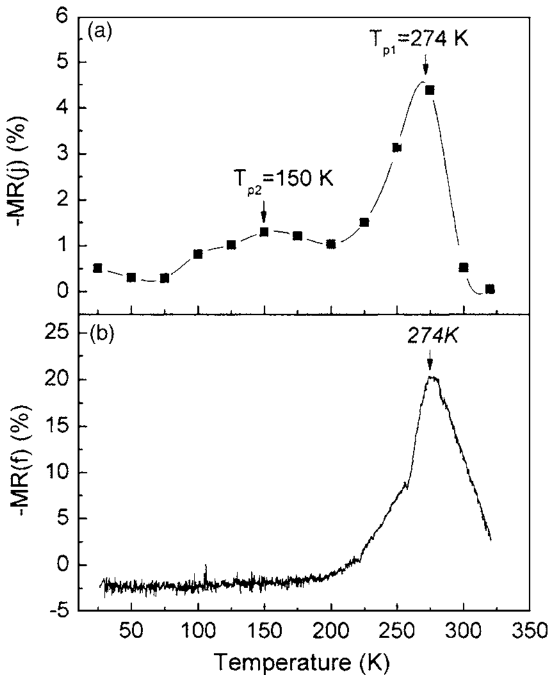

FIG. 5. Temperature dependent MR of (a) LCEM/STON heterojunction $\{[R_j(0)-R_j(H)]/R_j(0)\times 100\%\}$ and (b) LCEM film $\{[R_f(0)-R_f(H)]/R_f(0)\times 100\%\}$.

MR of the heterojunction to the variation of the resistances of the LCEM film and the depletion layer under the magnetic field. In order to separate the MR contribution of the LCEM film and the depletion layer to MR(j) of the heterojunction, the MR(f) of the LCEM film, defined as $\mathrm{MR}(f)=[(R_f(H)-R_f(0))/R_f(0)]$, is measured at $H=0.5$ T. The MR(f) as a function of the temperature is shown in Fig. 5(b). It shows that MR(f) has a maximum at $T=274$ K, which is the same temperature as T_{p1} as shown in Fig. 5(a). As an approximate method, we calculated $R_f(\sim 0.5\ \Omega)$ and $R_s(\sim 0.02\ \Omega)$ from their resistivities of LCEM film and STON substrate.[8] Therefore, the resistance of depletion layer R_d is about 90% of the resistance of junction R_j, and it is inaccordance with traditional p-n junctions. Therefore, combining Figs. 5(a) and 5(b), we attribute the MR(j) in the vicinity of T_{p1} to the contribution both from the MR(f) of the LCEM film ($\sim 2\%$) and MR(d) of the depletion layer ($\sim 2.5\%$). On the other hand, the MR(j) in the vicinity of T_{p2} should be ascribed to the contribution of the depletion layer only. As a result, the variation of the depletion layer under magnetic fields is suggested to be the underlying reason for the appearance of ΔV_{oc}.

As for the variation of the properties of the depletion layer under the applied magnetic fields, we think three factors to affect the depletion layer. The first factor is from LCEM film itself, because its magnetic state can be changed by the applied magnetic fields. As proven by various experiments,[1,9] the manganites undergo a change of band structure accompanying the paramagnetic to ferromagnetic (FM) transition, i.e., the spin-up and spin-down subbands split in FM state of LCEM. Under the action of external magnetic fields, the spin disorder around T_c is suppressed and the spin-polarized carriers tend to occupy the lower subbands, which results in the reduction of the Fermi level of LCEM. Therefore, the potential barrier between LCEM and STON is decreased. In other words, the depletion layer of LCEM/STON junction under external magnetic fields becomes effectively thinner, which results in the decrease of V_{oc}. This factor explains the appearance of ΔV_{oc} near the T_c because the reduction of Fermi level of LCEM and the potential barrier between LCEM and STON should only occur in the vicinity of T_c. However, the inset in Fig. 4 shows that the change in V_{oc} caused by the external magnetic field takes place in a wide temperature range from 20 to 300 K. Hence, other factors should be considered. One should be considered is that there exists some FM insulating phases, except for FM metallic phases in the depletion layer caused by the interface strain, i.e., there is phase separation in the interfacial region of the heterojunction as suggested by recent theoretical and experimental studies of manganites.[10,11] The fractions of both FM metallic and FM insulating phases can be changed by applied magnetic fields, which results in the variation of the depletion layer. Another one may be the change of canting angle of magnetic domains under magnetic fields. Based on our experimental results, it appears to be more reasonable to attribute the V_{oc} change induced by the applied magnetic field to the latter two factors. A further study on the manipulation of the depletion layer found in our work is underway.

In conclusion, a clear magnetic field effect on the photovoltage in a LCEM/STON heterojuntion is observed. Our results imply that it is possible to develop novel photovoltaic devices that can be modulated by magnetic fields.

This work is supported by the National Key Fundamental Research under Contract No. 001CB610604, and the National Nature Science Foundation of China under Contract Nos. 10174085, 10474100 and 10474133, and the Fundamental Bureau of Chinese Academy of Sciences.

[1] R. von Helmolt, J. Wecker, B. Holzapfel, L. Schultz, and K. Samwer, Phys. Rev. Lett. **71**, 2331 (1993); S. Jin, T. H. Tiefel, M. McCormack, R. A. Fastnacht, R. Ramesh, and L. H. Chen, Science **264**, 413 (1994); A. P. Ramirez, J. Phys.: Condens. Matter **9**, 8171 (1997); J. M. D. Coey, M. Viret, and S. von Molnar, Adv. Phys. **48**, 167 (1999); M. B. Salamon and M. Jaime, Rev. Mod. Phys. **73**, 583 (2001).
[2] H. Tanaka, J. Zhang, and T. Kawai, Phys. Rev. Lett. **88**, 027204 (2002).
[3] F. X. Hu, J. Gao, J. R. Sun, and B. G. Shen, Appl. Phys. Lett. **83**, 1869 (2003).
[4] J. M. D. Coey, M. Viret, and S. von Molnar, Adv. Phys. **48**, 167 (1999).
[5] J. R. Sun, C. M. Xiong, T. Y. Zhao, S. Y. Zhang, Y. F. Chen, and B. G. Shen, Appl. Phys. Lett. **84**, 1528 (2004).
[6] J. R. Sun, C. H. Lai, and H. K. Wong, Appl. Phys. Lett. **85**, 37 (2004).
[7] J. R. Sun, B. G. Shen, Z. G. Sheng, and Y. P. Sun, Appl. Phys. Lett. **85**, 3375 (2004).
[8] The resistivities of LCEM and STON are from the resistive measurement of the LCEM film and STON substrate, respectively.
[9] C. Mitra, P. Raychaudhuri, K. Dörr, K.-H. Müller, L. Schultz, P. M. Oppencer, and S. Wirth, Phys. Rev. Lett. **90**, 017202 (2003).
[10] J. Z. Sun, D. W. Abraham, R. A. Rao, and C. B. Eom, Appl. Phys. Lett. **74**, 3017 (1999).
[11] A. Moreo, A. Yunoki, and E. Dagotto, Science **282**, 2034 (1999).