Transparent ultraviolet photovoltaic cells

Article *in* Optics Letters · February 2016

DOI: 10.1364/OL.41.000685


Xun Yang
Chinese Academy of Sciences


Chong-Xin Shan
Chinese Academy of Sciences


Ying-Jie Lu
Zhengzhou University


Bing An Li
University of Kentucky

Optics Letters

Transparent ultraviolet photovoltaic cells

Xun Yang,[1,2] Chong-Xin Shan,[1,3,*] Ying-Jie Lu,[3] Xiu-Hua Xie,[1] Bing-Hui Li,[1] Shuang-Peng Wang,[1] Ming-Ming Jiang,[1] and De-Zhen Shen[1]

[1]State Key Laboratory of Luminescence and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]School of Physics and Engineering, Zhengzhou University, Zhengzhou 450001, China
*Corresponding author: shancx@ciomp.ac.cn

Received 3 November 2015; revised 25 December 2015; accepted 29 December 2015; posted 5 January 2016 (Doc. ID 252922); published 5 February 2016

Photovoltaic cells have been fabricated from *p*-GaN/MgO/*n*-ZnO structures. The photovoltaic cells are transparent to visible light and can transform ultraviolet irradiation into electrical signals. The efficiency of the photovoltaic cells is 0.025% under simulated AM 1.5 illumination conditions, while it can reach 0.46% under UV illumination. By connecting several such photovoltaic cells in a series, light-emitting devices can be lighting. The photovoltaic cells reported in this Letter may promise the applications in glass of buildings to prevent UV irradiation and produce power for household appliances in the future.

OCIS codes: (140.7240) UV, EUV, and X-ray lasers; (350.6050) Solar energy.

http://dx.doi.org/10.1364/OL.41.000685

Photovoltaic cells, which can convert light into electricity, have attracted much attention in recent years for their capability in reducing the consumption of fossil fuels and the release of carbon dioxide, thus are of great significance in reducing air pollution and global warming, the two global challenges that humans encounter nowadays [1–3]. Photovoltaic cells are usually designed and fabricated to utilize visible light, which is the major part of solar energy, to generate electricity. Since visible light is absorbed by the cells, traditional solar cells are usually opaque [4,5]. However, if transparent photovoltaic cells which utilize UV light as energy can be fabricated, they can be used as window glass of buildings or cars. Then the transparence of the glass will not be altered much, and may reduce the possible harm caused by UV irradiation to humans. The generated electricity may also be used to power household appliances.

ZnO is transparent to visible light and can absorb most ultraviolet light, which makes it an ideal choice to achieve transparent photovoltaic cells [6–8]. Moreover, ZnO has the advantages of low cost, simple preparation process, and can be prepared in a relatively large area, etc. [7–11]. Actually, ZnO has been widely used in CdTe, $CuInGaSe_2$, and dye-sensitized solar cells [12–16]. However, ZnO in these solar cells was used as window layers or transparent conductive layers. Using ZnO as absorber layers to fabricate transparent photovoltaic cells has not been reported before. To construct solar cells, a *p*-*n* junction is usually needed to separate the photogenerated electrons and holes. Unfortunately, ZnO is intrinsically an *n*-type semiconductor and high-quality *p*-type ZnO is still a challenging issue [9,17–19]. An alternative approach is to fabricate heterojunctions using other available *p*-type materials. Among many available *p*-type materials, GaN is considered to be the most promising one because it has the same wurtzite crystalline structure and very similar lattice constants with ZnO [9,20,21]. ZnO/GaN heterostructure-based light-emitting devices, photodetectors, and lasers have been demonstrated before, but no reports on UV photovoltaic cells on such structures can be found up to date [21–26].

In this Letter, photovoltaic cells have been fabricated from *p*-GaN/MgO/*n*-ZnO structures. The photovoltaic cells are transparent to visible light and show obvious photovoltaic effect under UV illumination. When the power density of the UV light (wavelength range from 300 to 400 nm) is $4.3\ mW/cm^{-2}$, the short-circuit current density, open-circuit voltage, fill factor, and power conversion efficiency of the photovoltaic cells are $0.214\ mA/cm^2$, 0.26 V, 36%, and 0.46%, respectively. A light-emitting diode can be driven by connecting several photovoltaic cells in a series, indicating the promise of the UV photovoltaic cells in powering household appliances.

The *p*-type GaN layer was grown on *c*-plane sapphire by molecular beam epitaxy (DCA P600) with an undoped GaN layer as a buffer layer. High-purity metallic gallium and magnesium contained in individual Knudsen effusion cells were used as the Ga source and Mg dopant source. The temperatures of the Ga source and Mg source were fixed at 1135°C and 340°C, respectively. Nitrogen cracked via an Oxford Applied Research HD25 radio-frequency atomic source was used as the N source. During the growth process, the substrate temperature was kept at 900°C and the N_2 flow rate was maintained at 3.34 sccm. The pressure in the growth chamber was fixed at 1.1×10^{-5} mbar. After the growth process, MgO and ZnO layers were grown onto the *p*-type GaN to form the GaN/MgO/ZnO structures. Metallic magnesium and zinc contained in individual Knudsen effusion cells were used as Mg and Zn sources. The temperatures of the Mg cell and Zn cell were fixed at 305°C and 210°C, respectively. Oxygen was used as the O source for the growth of the MgO and ZnO layer, and the gas source was activated by the Oxford Applied Research radio-frequency plasma cell operated at 300 W. During the growth process, the flow rate of oxygen gas was kept at 1.0 sccm and the pressure in the growth chamber was maintained at 3.9×10^{-6} mbar. Prior to the growth of ZnO, an MgO layer was deposited onto the *p*-type GaN layer with the substrate temperature at 400°C. Then the substrate temperature was increased to 700°C to grow the ZnO layer. When exposed to oxygen at a high temperature, GaN is likely to form a Ga_2O_3 interface layer [27,28]. This will produce interfacial defects which may capture photogenerated carriers, leading to impairment of the photovoltaic effect. This MgO layer was deposited onto *p*-GaN at a relative low temperature before the growth of ZnO to avoid the *p*-GaN layer being oxidized. The thickness of the MgO layer is only 15 nm and it will not hinder carrier transportation much. Metallic Ni/Au and In layers were deposited onto the *p*-type GaN and *n*-type ZnO acting as electrodes by thermal evaporation method, respectively. The electrical properties of the GaN and ZnO layer were evaluated by a Lakeshore 7707 Hall measurement system under van der Pauw configuration. The x-ray diffraction (XRD) was carried out in a Bruker D8 x-ray diffractometer. The thickness of the GaN, MgO, and ZnO layers was determined using a Hitachi S4800 field emission scanning electron microscope. Current density-voltage (*J-V*) characteristics of the photovoltaic cells were studied by an Agilent B1500A semiconductor device analyzer under simulated AM 1.5 illumination with intensity of 100 mW/cm^2, and a ZWB2 uviol glass was used to filter out the visible light. The light intensity was recorded using an OPHIR Nova II power meter. The optical absorption and transmission spectra of the samples were measured by a Shimadzu UV-3101PC spectrometer. The external quantum efficiency (EQE) of the *p*-GaN/MgO/*n*-ZnO photovoltaic cells was measured using a Xe lamp, monochromator, chopper, and lock-in amplifier.

Figure 1(a) shows the schematic diagram of the *p*-GaN/MgO/*n*-ZnO photovoltaic cells. The thickness of the GaN, MgO, and ZnO layers is about 1240, 15, and 140 nm, respectively. The hole concentration and Hall mobility of the *p*-GaN layer are 5.3×10^{17} cm^{-3} and 16.4 cm^2 V^{-1} s^{-1}, respectively. The electron concentration and Hall mobility of the *n*-ZnO are 3.4×10^{15} cm^{-3} and 1.7 cm^2 V^{-1} s^{-1}, respectively. The XRD pattern of the *p*-GaN/MgO/*n*-ZnO structures is shown in Fig. 1(b). Two peaks at 34.46° and 34.52° can be observed. The former can be identified as the diffraction from the (002) facet of wurtzite ZnO and the latter is from the (002) facet of GaN.

Figure 2 shows the *I-V* curve of the *p*-GaN/MgO/*n*-ZnO structures under dark conditions. Obvious rectifying characteristics can be observed from the structures, revealing that photovoltaic behavior may be obtained in these structures.

The absorption and transmission spectra of the *p*-GaN/MgO/*n*-ZnO structures are shown in Fig. 3. It can be observed that the structures have a sharp absorption edge at around 377 nm, which corresponds to the bandgap of ZnO [7]. The absorption is fluctuant between 200 and 350 nm, which is mainly due to the precision of the spectrometer at this range. The average transmission of the *p*-GaN/MgO/*n*-ZnO structures in the visible spectrum region is about 90%. Note that the fluctuation in the spectra is due to the interference of the illumination light in the multilayers. The inset of Fig. 3 shows the optical image of a *p*-GaN/MgO/*n*-ZnO structure; one can see that the structure shows good transparency, promising their application in transparent UV photovoltaic cells.

Figure 4(a) shows the current density-voltage (*J-V*) curves of the *p*-GaN/MgO/*n*-ZnO structures under dark conditions and the illumination of simulated AM 1.5 solar spectrum (100 mW/cm^2). The *J-V* characteristic of the *p*-GaN/MgO/*n*-ZnO structures exhibits an open-circuit voltage of 0.28 V, a short-circuit current density of 0.258 mA/cm^2, and a fill factor of 34.6%, which led to an overall efficiency of 0.025%. It is notable that the efficiency is relatively low. This is because the

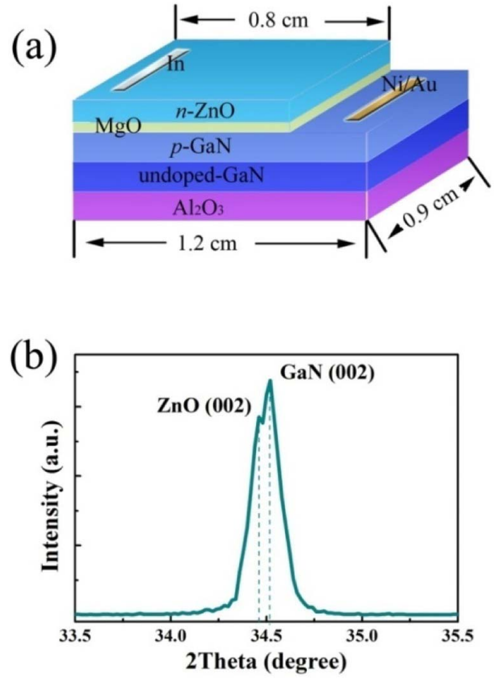

Fig. 1. (a) Schematic diagram and (b) XRD pattern of the *p*-GaN/MgO/*n*-ZnO structures.

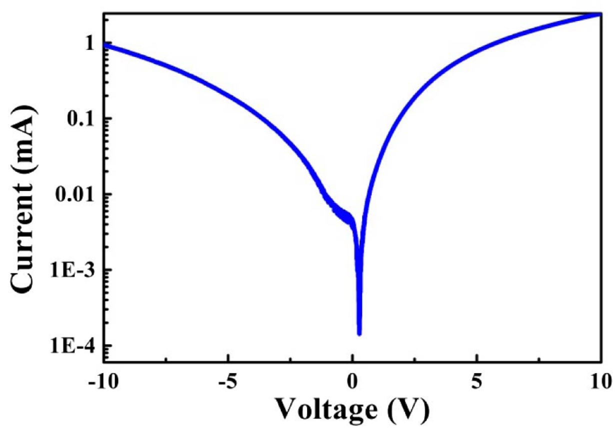

Fig. 2. *I–V* curve of the *p*-GaN/MgO/*n*-ZnO structures under dark conditions.

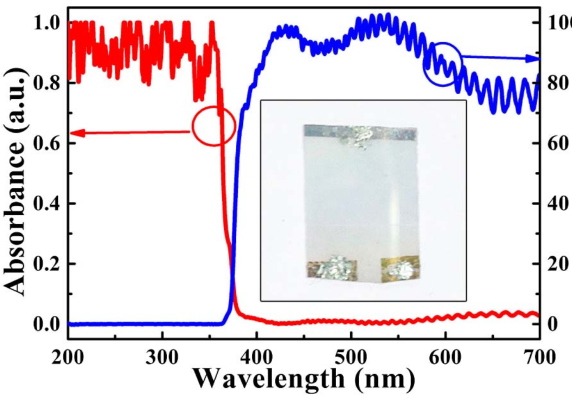

Fig. 3. Absorption and transmission spectra of the *p*-GaN/MgO/*n*-ZnO photovoltaic cells. The inset shows the optical image of the photovoltaic cell.

p-GaN/MgO/*n*-ZnO structures are transparent to visible light, as shown in Fig. 3(a), and only UV light can be absorbed. To confirm the above explanation, a ZWB2 filter was employed to filter out visible light. The inset of Fig. 4(b) shows the transmission spectrum of the filter. One can see that the filter is only transparent to light with a wavelength between 300 and 400 nm, and the power density of the transmission light is about 4.3 mW/cm^2. The *J-V* curve under simulated AM 1.5 illuminations with the filter was also measured, as shown in Fig. 4(b). The short-circuit current density, open-circuit voltage, fill factor, and efficiency of the photovoltaic cells are 0.214 mA/cm^2, 0.26 V, 36%, and 0.46%, respectively, as indicated in Table 1.

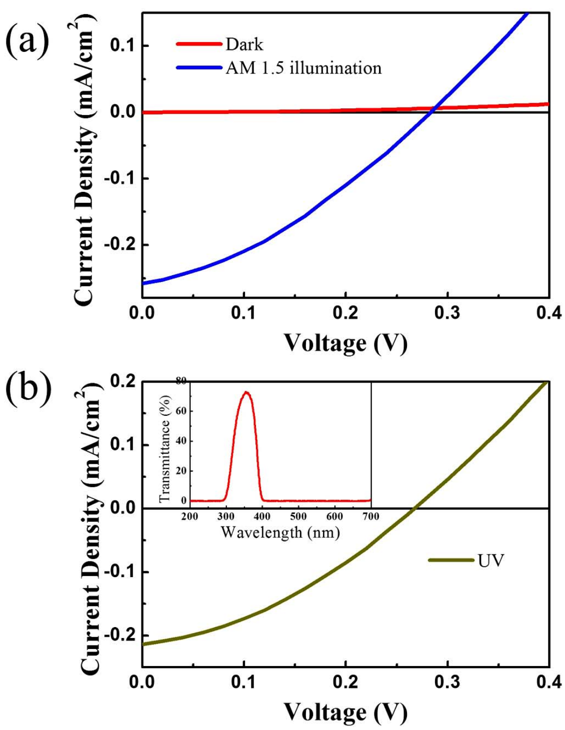

Fig. 4. *J-V* curves of the *p*-GaN/MgO/*n*-ZnO structures under dark conditions, (a) simulated AM 1.5 illuminations and (b) under simulated AM 1.5 illuminations with ZWB2 filter. The inset of (b) shows the transmission spectrum of the ZWB2 filter.

Table 1. Performance Parameters of the *p*-GaN/MgO/*n*-ZnO Photovoltaic Cells Under Simulated AM 1.5 Illumination (100 mW/cm^2) with and without the ZWB2 Filter

	Jsc (mA/cm^2)	V_{OC} (V)	FF (%)	Light Intensity (mW/cm^2)	Efficiency (%)
AM 1.5	0.258	0.28	34.6	100	0.025
UV	0.214	0.26	36.0	4.3	0.46

The EQE of the *p*-GaN/MgO/*n*-ZnO photovoltaic cells is shown in Fig. 5. The EQE increases rapidly when the wavelength is shorter than 372 nm, which corresponds to the absorption edge of the *p*-GaN/MgO/*n*-ZnO photovoltaic cells. The EQE is larger than 10% for the light shorter than 352 nm.

Finally, to confirm the potential application of the photovoltaic cells, we use the photovoltaic cells to drive a LED. A mercury lamp was used as the UV radiation for the photovoltaic cells. The central wavelength and light intensity of the lamp were 365 nm and 12.8 mW/cm^2, respectively. Ten photovoltaic cells were connected in series to form a battery pack. Under the illumination of the UV radiation, the total open circuit of this series of photovoltaic cells can reach 2.26 V. When a LED was connected to the circuit, obvious red light could be observed from the LED, as shown in Fig. 6. The above results indicate that if these transparent photovoltaic cells can be used as the window glass of buildings, they will not only protect people from UV irradiation but also can supply electric power for household appliances.

Here we have to note that the device performance is still poor compared with traditional solar cells. We think the performance of the devices is mainly limited by the defects at the ZnO/GaN interface. The defects will reduce the carrier diffusion length, and thus lead to high reverse saturation current. This will reduce the open-circuit voltage and short-circuit current, and thus reduce the device performance. One can thus expect that the device performance can be improved by reducing the defects at the interface.

In summary, photovoltaic cells have been fabricated from *p*-GaN/MgO/*n*-ZnO structures. The photovoltaic cells are

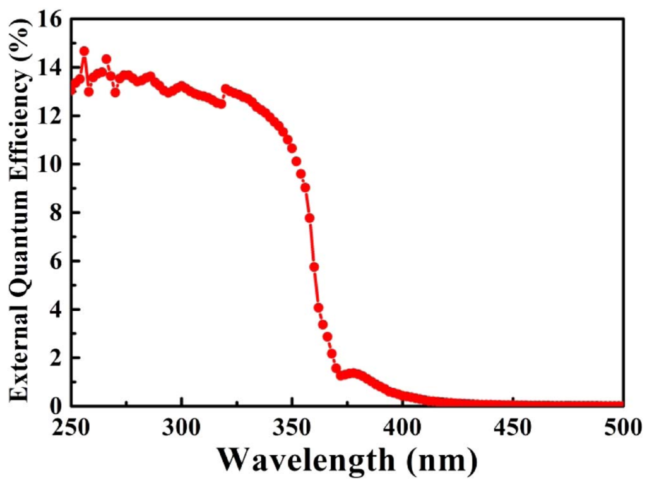

Fig. 5. External quantum efficiency of the *p*-GaN/MgO/*n*-ZnO photovoltaic cells.

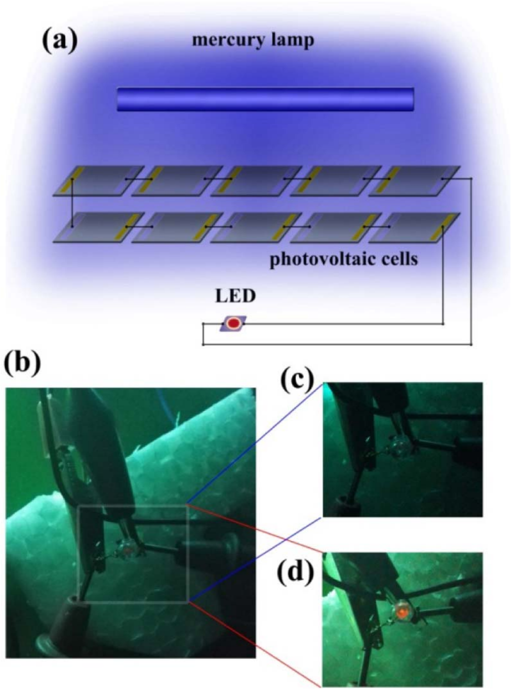

Fig. 6. (a) Schematic diagram and (b) optical image of the photovoltaic cells drive a red LED under the illumination of mercury lamp. (c) and (d) show the images of the LED when the mercury lamp is off and on, respectively.

transparent to visible light and can absorb and transform UV light into electric energy. Under the illumination of UV light, obvious photovoltaic effect can be observed. The power conversion efficiency of the photovoltaic cells is 0.025% under simulated AM1.5 illumination conditions, while it can reach 0.46% under UV illumination. By connecting several photovoltaic cells in a series, a LED can be driven. Although the performance of the cells still needs improving, the photovoltaic cells demonstrated in this Letter may be used as window glass for buildings, cars, and screens to absorb ultraviolet light and produce electrical energy but not affect the day-lighting in the future.

Funding. National Science Foundation for Distinguished Young Scholars of China (61425021); National Natural Science Foundation of China (NSFC) (11374296, 11134009, 11404328).

REFERENCES

1. H. Bao and X. L. Ruan, Opt. Lett. **35**, 3378 (2010).
2. F. Wang, H. Y. Yu, J. S. Li, F. Padinger, X. W. Sun, X. C. Wang, and H. Y. Zeng, Opt. Lett. **35**, 40 (2010).
3. G. Yu, J. Gao, J. C. Hummelen, F. Wudl, and A. J. Heeger, Science **270**, 1789 (1995).
4. H. Zhou, Q. Chen, G. Li, S. Luo, T. B. Song, H. S. Duan, Z. Hong, J. B. You, Y. Liu, and Y. Yang, Science **345**, 542 (2014).
5. Z. C. He, C. M. Zhong, S. J. Su, M. Xu, H. B. Wu, and Y. Cao, Nat. Photonics **6**, 591 (2012).
6. D. C. Look, Mater. Sci. Eng. B **80**, 383 (2001).
7. X. Y. Liu, C. X. Shan, C. Jiao, S. P. Wang, H. F. Zhao, and D. Z. Shen, Opt. Lett. **39**, 422 (2014).
8. R. L. Hoffman, J. Appl. Phys. **95**, 5813 (2004).
9. J. C. Fan, K. M. Sreekanth, Z. Xie, S. L. Chang, and K. V. Rao, Prog. Mater. Sci. **58**, 874 (2013).
10. M. Dutta and D. Basak, Appl. Phys. Lett. **92**, 212112 (2008).
11. J. M. Ntep, S. S. Hassani, A. Lusson, A. Tromson-Carli, D. Ballutaud, G. Didier, and R. Triboulet, J. Cryst. Growth **207**, 30 (1999).
12. Z. Q. Liu, X. H. Xie, Q. Z. Xu, S. H. Guo, N. Li, Y. B. Chen, and Y. Z. Su, Electrochim. Acta **98**, 268 (2013).
13. X. N. Wang, H. J. Zhu, Y. M. Xu, H. Wang, Y. Tao, S. Hark, X. D. Xiao, and Q. A. Li, ACS Nano **4**, 3302 (2010).
14. K. Ramanathan, M. A. Contreras, C. L. Perkins, S. Asher, F. S. Hasoon, J. Keane, D. Young, M. Romero, W. Metzger, R. Noufi, J. Ward, and A. Duda, Prog. Photovoltaics **11**, 225 (2003).
15. P. Suri, M. Panwar, and R. M. Mehra, Mater. Sci.-Poland **25**, 137 (2007).
16. A. D. Goncalves, M. R. Davolos, and A. F. Nogueira, J. Nanosci. Nanotechnol. **10**, 6432 (2010).
17. M. T. Chen, M. P. Lu, Y. J. Wu, J. Song, C. Y. Lee, M. Y. Lu, Y. C. Chang, L. J. Chou, Z. L. Wang, and L. J. Chen, Nano Lett. **10**, 4387 (2010).
18. S. Chu, J. Zhao, Z. Zuo, J. Kong, L. Li, and J. Liu, J. Appl. Phys. **109**, 123110 (2011).
19. D. C. Look, G. M. Renlund, R. H. Burgener, and J. R. Sizelove, Appl. Phys. Lett. **85**, 5269 (2004).
20. Y. J. Lu, H. F. Li, C. X. Shan, B. H. Li, D. Z. Shen, L. G. Zhang, and S. F. Yu, Opt. Express **22**, 17524 (2014).
21. H. Zhang, R. Shen, H. Liang, Y. Liu, Y. Liu, X. Xia, and G. Du, J. Phys. D **46**, 065101 (2013).
22. J. J. Hassan, M. A. Mahdi, Y. Yusof, H. Abu-Hassan, Z. Hassan, H. A. Al-Attar, and A. P. Monkman, Opt. Mater. **35**, 1035 (2013).
23. J. Dai, C. X. Xu, and X. W. Sun, Adv. Mater. **23**, 4115 (2011).
24. H. Zhu, C. X. Shan, B. Yao, B. H. Li, J. Y. Zhang, D. X. Zhao, D. Z. Shen, and X. W. Fan, J. Phys. Chem. C **112**, 20546 (2008).
25. Y. Q. Bie, Z. M. Liao, H. Z. Zhang, G. R. Li, Y. Ye, Y. B. Zhou, J. Xu, Z. X. Qin, L. Dai, and D. P. Yu, Adv. Mater. **23**, 649 (2011).
26. H. Zhu, C. X. Shan, B. Yao, B. H. Li, J. Y. Zhang, Z. Z. Zhang, D. X. Zhao, D. Z. Shen, X. W. Fan, Y. M. Lu, and Z. K. Tang, Adv. Mater. **21**, 1613 (2009).
27. S. K. Hong, H. J. Ko, Y. F. Chen, T. Hanada, and T. Yao, Appl. Surf. Sci. **159**, 441 (2000).
28. S. K. Hong, T. Hanada, H. J. Ko, Y. Chen, and T. Yao, Phys. Rev. B **65**, 115331 (2002).