第22卷第6期 半 导 体 学 报 Vol. 22, No. 6
2001年6月 CHINESE JOURNAL OF SEMICONDUCTORS June, 2001

Proton Irradiation and Thermal Annealing of GaAs Solar Cells*

XIANG Xian-bi[1], DU Wen-hui[1], LIAO Xian-bo[2] and CHANG Xiu-lan[1]

(1 *Laboratory of Semiconductor Materials Science, Institute of Semiconductors, The Chinese Academy of Sciences, Beijing 100083, China*)

(2 *State Key Laboratory for Surface Physics, Institute of Semiconductors, The Chinese Academy of Sciences, Beijing 100083, China*)

Abstract: The investigation on proton irradiation and thermal annealing of AlGaAs/GaAs solar cells has been reported. The energy of the proton irradiation is 325keV and the fluences are ranging from 5×10^{10} to 1×10^{13}cm^{-2}. It is demonstrated that the irradiation-induced degradation in the photovoltaic performance of the solar cells exists mainly in the short circuit current and the irradiation damage can be partly recovered by low temperature annealing at 200℃. In addition, it is found that the borosilicate cover glass has an obvious protection effect against the proton irradiation.

Key words: proton irradiation; thermal annealing; solor cell

EEACC: 8420

CLC number: TM914.4 **Document code**: A **Article ID**: 0253-4177(2001)06-0710-05

1 Introduction

Much attention has been paid to GaAs solar cells in recent years, owing to their advantages in space applications, compared with silicon solar cells, such as greater radiation hardness, which is very important for their application in the space environment.

The AlGaAs/GaAs solar cells have been studied for many years. The conversion efficiency of AlGaAs/GaAs solar cells prepared by using a multi-wafers LPE technique was obtained to be 19.34% (AM0, 4.4cm^2, 25℃) in 1996[1,2], while that of the cells prepared by MOCVD technique was up to 21.95% (AM0, 2cm × 2cm, 25℃) in 1999[3], with a typical I-V characteristic shown in Fig. 1. In order to understand the change in the photovoltaic parameters of the cells in space application, it is important to study the irradiation effect on the performance of AlGaAs/GaAs solar cells, which is induced by high energy particles, especially the high energy electrons and protons[4]. 3MeV electron irradiation experiments and 625keV proton irradiation experiments on AlGaAs/GaAs solar cells have been performed in the past years[5,6]. Due to the great fluence of proton irradiation used in our previous work that is ranging from 1×10^{14} to 5×10^{15} cm^{-2}, the photovoltaic performance of the solar cells was nearly completely destroyed by the proton irradiation[6]. Therefore, a new set of proton irradiation experiments has been carried out on AlGaAs/GaAs solar cells with a proton energy of 325keV and much lower irradiation fluences ranging from 5×10^{10} to 1×10^{13}cm^{-2}, the annealing effect on irradiated solar cells have also been conducted. The main results obtained in the recent proton irradiation and annealing experiments are reported in this paper.

* Project Supported National Natural Science Foundation of China.

Received 17 March 2000, revised manuscript received 29 September 2000

©2001 The Chinese Institute of Electronics

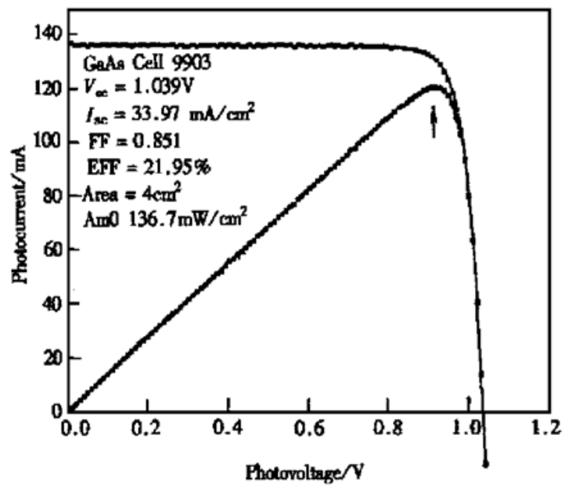

FIG. 1 Typical Illuminated I-V Characteristics of MOCVD GaAs Solar Cells with Photovoltaic Parameters of V_{oc}= 1.039V, I_{sc}= 33.97mA/cm^2, FF= 0.851 and η= 21.95% (AM0, 136.7mW/cm^2, 2cm × 2cm)

2 Experiments

2.1 Preparation of GaAs Solar Cells

GaAs solar cells used in this study were grown by using a multi-wafers LPE technique and a two-step epitaxial process[1], with a p^+-$Al_xGa_{1-x}As/p^+$-GaAs/n-GaAs/n^+-GaAs substrate. The n^+-substrate is Si-doped with the concentration of $1\times10^{18}cm^{-3}$ and orientation of (100). The n-buffer layer and the p^+-$Al_xGa_{1-x}As$ window layer are grown via two different processes and doped by Sn and Zn separately. The concentration and thickness of n-buffer layer are $2\times10^{17}cm^{-3}$ and about 20μm, respectively, while those of p^+-$Al_xGa_{1-x}As$ window layer are $2\times10^{18}cm^{-3}$ and 0.5μm, respectively, when the composition of Al, x, is about 0.8. The p^+-GaAs emitter layer is formed in the n-buffer layer due to Zn atoms diffusing from AlGaAs layer during the epitaxial growth process for the window layer. The concentration of p^+-GaAs layer is $2\times10^{18}cm^{-3}$, and the thickness, varying from 0.5μm to 2.5μm, depends on the growth temperature.

The contacts are formed by photolithography, vacuum evaporation and electroplating. The front contact is TiAu and the back contact is AuGeNi. The antireflection coating is an anodized film of AlGaAs layer, formed by using electron-chemical method. The GaAs solar cells used in the irradiation experiments are specially designed, with the area of 0.5cm × 0.5cm. Though the conversion efficiency can reach 20.03% (AM0, 25℃), the average efficiencies of the cells used for irradiation experiments are 16% (AM0) or so.

2.2 Irradiation Experiments

The proton irradiation experiments were performed at room temperature with ion-implantation equipment in Beijing Normal University. The energy of the proton adopted was 325keV and the fluences ranged from 5×10^{10} to $1\times10^{13}cm^{-2}$.

Two groups of samples were irradiated at the same time. The samples in Group one have small junction-depth of about 1.4μm, while those in Group two have larger junction-depths of about 2.6μm. In the irradiation experiments, four samples with larger junction-depths and six with small junction-depths were covered by borosilicate glass, which were used to test the protection effect of borosilicate glass against the proton irradiation.

2.3 Thermal Annealing

Investigation on the thermal annealing behavior of the proton irradiated cells is of every significance[4]. Thermal annealing experiments have been made for all irradiated GaAs solar cells to test the recovery ability of radiation damage by thermal annealing in N_2 flow at a relatively low temperature (from 150℃ to 300℃) for 30min.

3. Measurements and Results

3.1 Photovoltaic Performance Measurement

The I-V characteristics of the GaAs solar cells were measured with a solar simulator (AM0,

$100mW/cm^2$, 1Sun) before and after irradiation. All the photovoltaic parameters of the cells after irradiation, including the open circuit voltage (V_{oc}), short circuit current (I_{sc}), fill factor (FF), and conversion efficiency (η) were normalized by the initial values for the purpose of comparison.

In comparison with the results of electron irradiation experiments[5], the proton irradiation causes more serious damages in the GaAs solar cells. Figures 2(a), (b) and (c) demonstrate the normalized values of V_{oc}, I_{sc} and FF, respectively, as a function of the proton irradiation fluences of 5×10^{10}—$1\times 10^{13}cm^{-2}$ for both the shallow and deep junction cells. It is seen that the photovoltaic parameters of the shallow junction cells are not degraded significantly due to the proton irradiation, even when the fluence of proton is up to $5\times 10^{12}cm^{-2}$, but the photovoltaic parameters of the deep junction cells decrease obviously with the proton fluences, especially the normalized I_{sc} of the deep junction cells are lowered down to 0.2 even at the low fluence of $5\times 10^{10}cm^{-2}$. However, the borosilicate glass exhibits an excellent protection effect against the proton irradiation. The normalized I_{sc} of all cells covered by borosilicate glass is not changed obviously in the whole fluence range for both types of cells, as shown in Fig. 2(b).

Figures 3(a), (b) and (c) show the effect of thermal annealing at 200℃ on the photovoltaic parameters of V_{oc}, I_{sc} and FF of the proton-irradiated cells, respectively. It is seen that the normalized I_{sc} of the shallow junction cells, which have been irradiated at the proton fluence of $1\times 10^{13}cm^{-2}$ first and then annealed, recovers from about 0.3 to 0.7, while the normalized I_{sc} of the deep junction cells is not obviously improved by the annealing at 200℃. It is unexpected that the normalized FF of some cells are recovered beyond 1 after the annealing, seen in Fig. 3(c).

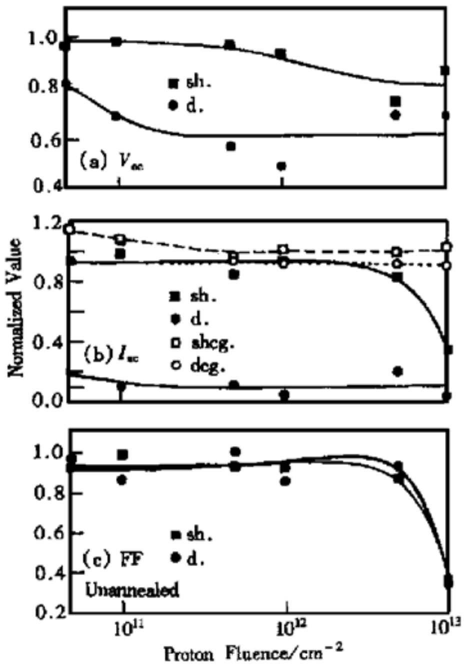

FIG. 2 Changes of Normalized Photovoltaic Parameters of the 325keV Proton Irradiated GaAs Solar Cells of Shallow and Deep Junction with Proton Fluences (a) Open Circuit Voltage; (b) Short Circuit Current; (c) Fill Factor The "cg" in the legend means "with cover glass protection".

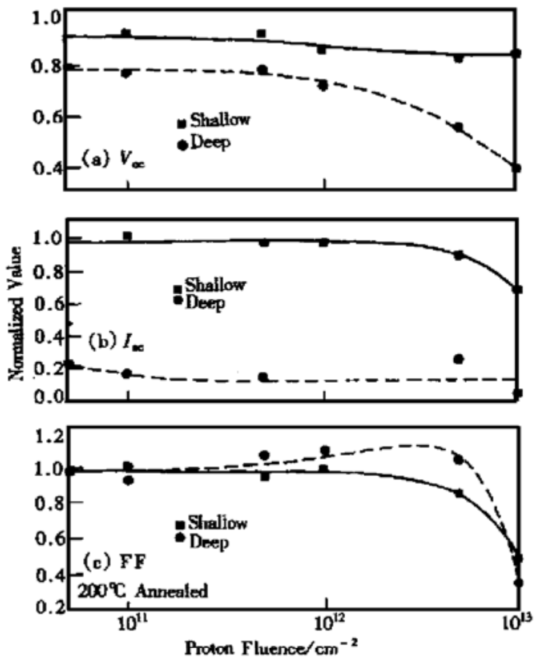

FIG. 3 Effect of Thermal Annealing at 200℃ on Proton Irradiated GaAs Solar Cells with Shallow and Deep Junction (a) Open Circuit Voltage; (b) Short Circuit Current; (c) Fill Factor

3.2 Calculation of Relative Damage Coefficient

The relative damage coefficient (D) of the proton irradiation to the electron irradiation is defined as follows[7],

$$D = F_e(r)/F_p(r), \quad (1)$$

where $F_e(r)$ is the electron irradiation fluences, $F_p(r)$ denotes the proton irradiation fluence at the same normalized damage values (r) of the photovoltaic parameters. From the value of I_{sc} reported above for 325keV proton irradiation and in our previous work for 3MeV electron irradiation[5], the relative damage coefficient D of the GaAs solar cells is deduced to be about 100, with the norma-lized damage value (r) of I_{sc}, ranging from 0.9 to 0.7.

4 Discussion and Conclusion

Some experimental results need to be discussed further. Firstly, the thermal annealing effect on the irradiated cells is stronger than what we expect. For deep junction cells, some normalized values of FF are beyond 1, as shown in Fig. 3(c). Similar results have also been obtained in the study of electron irradiation on GaAs solar cells[5], as can be explained as follows: the thermal annealing process can not only eliminate all electrically active irradiation induced-damage centers, but also improve the perfection of the material lattice. As a result, the fill factor of the cells is increased. In addition, the contact resistance of the cells is also decreased after annealing, which can contribute to the increase in the efficiency of solar cells. Though this phenomenon is similar to that reported in our previous work[2], it is not consistent with the results of DLTS measurements[6]. This might be due to the the reason that some deep levels induced by proton irradiation are not electrically active. We will investigate the cause of this effect further.

The second phenomenon under discussion is the protection effect of borosilicate glass against irradiation. It is seen clearly from Fig. 2 (b) that the protection effect of borosilicate glass is obvious in proton irradiation. The normalized I_{sc} of the cells covered by borosilicate glass decreases rather small (dot line). But in electron irradiation, the protection effect of borosilicate glass is not significant, as published before[5]. It may be due to the fact that the electrons have small mass, so the incident electrons can penetrate much deeper than protons. It is reported that the penetrating depth of 3MeV electrons is about 1cm, which is much greater than the thickness of the borosilicate glass, therefore the cover glass (0.5mm thick) can not protect GaAs cells from electron irradiation. However, due to the great mass, the proton can only penetrate GaAs materials a few microns (μm), so the borosilicate cover glass of 0.5mm is thick enough to protect the GaAs solar cells against the proton irradiation.

Acknowledgment The authors would like to thank Xie liqing, Cheng Ruyi, Lu liwu and Zhang Yanhua for their help in the irradiation experiment and DLTS measurement.

References

[1] Xiang Xianbi, Fei Xueying, Xu Ying and Li Biao, A Multi-wafers LPE Technique for $Al_xGa_{1-x}As$/GaAs Heterojunction Solar Cells, Solar Energy Materials and Solar Cells, 1994, **35**(1—4): 69.

[2] Xiang Xianbi, Du Wenhui, Chang Xiulan and Liao Xianbo, Improvement of Parameters in GaAs Solar Cells by Low Temperature Annealing, Proc. of 14th European Photovoltaic Solar Energy Conf., 1997, III: 1774.

[3] X. B. Xiang, W. H. Du, X. L. Chang and H. R. Yuan, The Study on High Efficient AlGaAs/GaAs Solar Cells, Solar Energy Material and Solar Cells, 2001, **68**: 97—103.

[4] Robert Y. Loo, G. Sanjiv, Kamath and Sheng S. Li, Radiation Damage and Annealing in GaAs Solar Cells. IEEE Trans. Electron Devices, 1990, **37**(2): 485.

[5] Xiang Xianbi, Du Wenhui, Chang Xiulan and Liao Xianbo, Electron Irradiation and Thermal Annealing Effect on GaAs Solar Cells, Solar Energy Materials and Solar cells, 1998, **55**: 313.

[6] Xiang Xianbi, Liao Xianbo, Du Wenhui, Li Biao and Chang Xiulan, Proton Irradiation Effect on High Efficient AlGaAs/GaAs Solar Cells, Chinese Journal of Electronics, 1996, **5**

(2): 36.
[7] Takashi Noguchi and Masato Vesugi, Electron Energy Dependence of Relative Damage Coefficient of Silicon Solar Cells for Space Use, Technical Digest of the International PVSEC-5, 1990, 557.

GaAs 太阳电池的质子辐照和退火效应*

向贤碧[1] 杜文会[1] 廖显伯[2] 常秀兰[1]

(1 中国科学院半导体研究所 半导体材料科学实验室, 北京 100083)
(2 中国科学院半导体研究所 表面物理国家实验室, 北京 100083)

摘要: 对 AlGaAs/GaAs 太阳电池进行了质子辐照和热退火实验. 质子辐照的能量为 325keV, 辐照的剂量为 5×10^{10}—$1\times10^{13}cm^{-2}$. 实验结果表明, 质子辐照造成了 GaAs 太阳电池光伏性能的退化, 其中短路电流的退化比其它参数的退化更为明显. 退火实验结果表明, 200℃的低温退火可以使得辐照后的电池的光伏性能得以部分恢复. 此外, 实验结果还指出, 在 GaAs 太阳电池表面加盖一层 0.5mm 的硼硅玻璃盖片可以明显地减少质子辐照对 GaAs 太阳电池性能的损伤.

关键词: 质子辐照; 热退火; 太阳电池

EEACC: 8420

中图分类号: TM914.4 **文献标识码**: A **文章编号**: 0253-4177(2001)06-0710-05

* 国家自然科学基金资助项目.

2000-03-17 收到, 2000-09-29 定稿

©2001 中国电子学会