Proton radiation effect on GaAs/AlGaAs core–shell ensemble nanowires photo-detector

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We demonstrate that the GaAs/AlGaAs nanowires (NWs) ensemble is fabricated into photo-detectors. Current–voltage (*I–V*) characteristics are measured on GaAs/AlGaAs core–shell ensemble NW photo-detectors at room-temperature before and after 1-MeV proton irradiation with fluences from 1.0×10^{13} cm^{-2} to 5.0×10^{14} cm^{-2}. The degradation of photocurrent suggests that the point defects induced by proton radiation could cause both carrier lifetime and carrier mobility to decrease synchronously. Comparing with a GaAs quantum well, the degradations of light and dark current for the irradiated NWs photo-detector indicate that NWs material is a preferable potential candidate for space applications.

Keywords: radiation effect, lifetime damage coefficient, mobility damage coefficient, radiation damage

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1. Introduction

There has been a fast development and application of GaAs nanowires (NWs) in optoelectronics with recent advances in NW growth and fabrication techniques. It is important to study the radiation tolerances of optoelectronic nano-devices for atomic energy and space-based applications. GaAs/AlGaAs core–shell NWs have been widely studied in a broad range of optoelectronic devices, such as light-emitting diodes,[1] laser diodes,[2,3] solar cells,[4,5] and photodetectors[6,7] working towards the energy conservation as well as environment protection. Moreover, GaAs offers relatively high efficiency and the possibility of higher radiation resistance as an alternative material to silicon,[8] with overall better performance.[9] Despite these advances, still an uncertainty persists in the roles of point and cluster defects that may be present at exceedingly high density which may destroy the semiconductor devices in the presence of a radiation environment, such as space and an atomic energy field. Because materials used in the units relating to the radiation environment mentioned above must withstand long-term operation in strong radiation fields, it is well known that nano-material and nano-devices, such as quantum dot[10] and quantum well,[11] possess radiation hardness intrinsically.[12–15] However, nano-material has a relatively profound radiation effect, which derives from its nano-structure combining unique electronic and optoelectronic properties. Although the proton irradiation-induced intermixing effect in GaAs–AlGAs quantum well has been investigated by Tan *et al.*,[16–18] an essential explanation of understanding has not been explored yet due to a lack of systemized theory and data studied on GaAs NWs. Therefore, it is significant to develop the radiation effect on NWs theoretically and experimentally in order to understand this corresponding area. In this work, the *I–V* characteristic measurements are carried out to study the proton induced damage to GaAs/AlGaAs core–shell ensemble NWs-fabricated photo-detectors.

2. Experimental details

All the samples and equipment used in this study were provided/supported by the Semiconductor Optoelectronics and Nanotechnology Group of the Department of Electronic Material Engineering, Australian National University. The growth of GaAs/AlGaAs core–shell NWs, morphology and characteristics have been described by Joyce *et al.*[19] and Jiang *et al.*[20] GaAs/AlGaAs/GaAs core–shell–cap NWs grew on a p+-doped GaAs, and targeted for NWs with a nominal height of ~ 3 μm and diameter of 50 nm for the NWs core in this work.

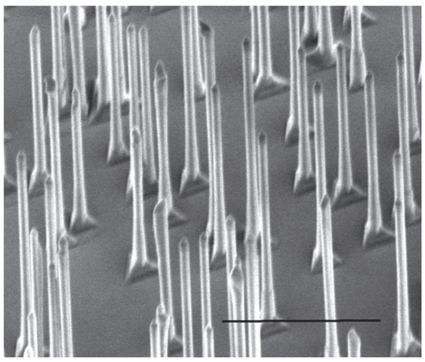


Fig. 1. SEM image of GaAs/AlGaAs/GaAs core–shell–cap NWs grown vertically on p^+-doped GaAs substrate. Scale bar is 2 μm.

The scanning electron microscope (SEM) image of the NWs is shown in Fig. 1. The NW photo-detectors fabrica-

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tion and proton irradiation process have been mentioned in Ref. [21]. One point which should be emphasized is that all measurements after irradiation were performed without an annealing process. Dark and light *I*–*V* characteristics of the NW photo-detectors at room-temperature were measured by using a 250-Watt tungsten lamp as the white illumination source (for light *I*–*V*) and a KEYSIGHT B2902A precision source. The irradiation fluence (φ) was in a range from 1.0×10^{13} cm^{-2} to 5×10^{14} cm^{-2} in this study.

3. Results and discussion

The radiation effects on the photocurrent and dark current of a GaAs/AlGaAs core–shell NWs photo-detector at room temperature of 1-MeV protons are shown in Figs. 2(a) and 2(b), respectively. With the increase of fluence, the number of defects rises, which causes more carriers to be trapped, thereby weakening the thermal transition process. This is reflected in the curves in Fig. 2(b) which shows that the dark current for the device decreases with irradiation fluence. However, defects generated from irradiation are also able to capture the photo-generated carriers which will then lead to lower photocurrent.[21]

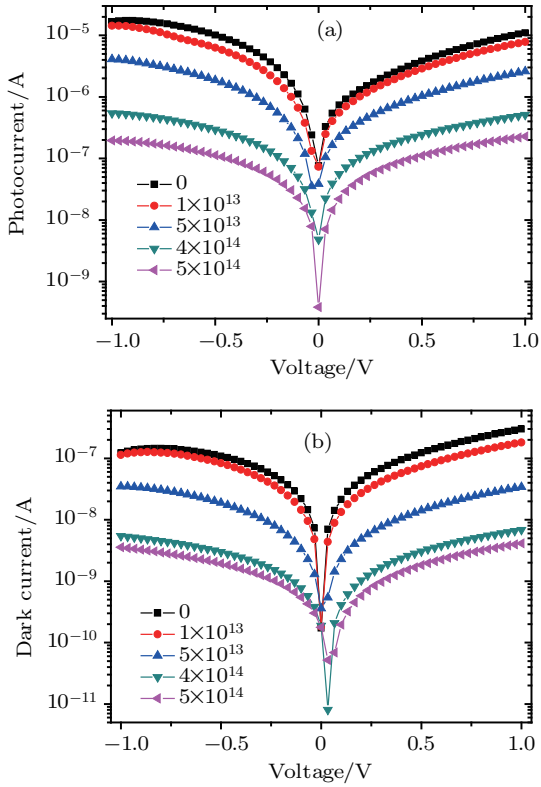


Fig. 2. (color online) Plots of (a) light and (b) dark *I*–*V* characteristics versus voltage at a 1-MeV proton irradiation fluence for the GaAs/AlGaAs/GaAs core/shell/cap NW photo-detector.

On the other hand, figure 2(a) shows that with increasing irradiation fluence, the photocurrent is reduced. Both dark conductivity and photoconductivity measurements were carried out by measuring the DC current with applied bias 1 V. The dark conductivity and photoconductivity versus proton irradiation fluence are displayed in Fig. 3.

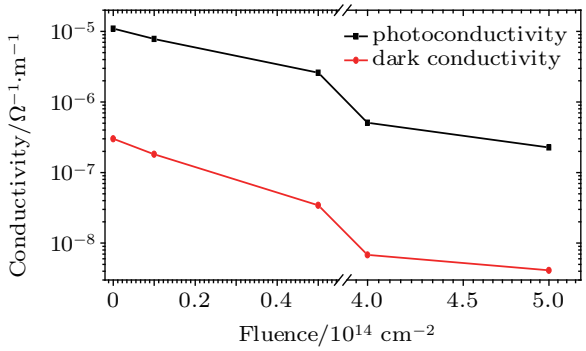


Fig. 3. (color online) Plots of measured dark conductivity and photoconductivity versus irradiation fluence at applied bias 1 V for the NW photo-detector. The fluence at 0 means the conductivity of pre-irradiation.

To directly study the radiation tolerance of the NWs photo-detector in terms of device performance, the operability of devices, which could be determined by the photocurrent reduction, is defined and used to evaluate the degradation degree (shown in the following Fig. 4). Technically the reduction of photocurrent could be used for representing the merits of the photo-detector, such as photoconductivity and responsivity with respect to those of post-irradiation. Because $I_{\rm ph}(\varphi)/I_{\rm ph}(0)=\sigma_{\rm ph}(\varphi)/\sigma_{\rm ph}(0)=R_\lambda(\varphi)/R_\lambda(0)\approx\tau(\varphi)\mu/\tau_0\mu_0$, where $I_{\rm ph}(\varphi)$ and $I_{\rm ph}(0)$ denote the post- and pre-irradiation photocurrent respectively, $\sigma_{\rm ph}(\varphi)$ and $\sigma_{\rm ph}(0)$ are the post and pre-irradiation photoconductivity respectively, $\tau(\varphi)$ and τ_0 the post and pre-irradiation lifetime respectively, $R_\lambda(\varphi)$ and $R_\lambda(0)$ the post and pre-irradiation responsivity, respectively. Accordingly, the definition of responsivity is the ratio of the photocurrent $I_{\rm ph}$ to the incident light power P_λ at a given wavelength and given by $R_\lambda=I_{\rm ph}/P_\lambda$.

The decrease in minority carrier lifetime causes several important optoelectronic device characteristics to change, such as light current, responsivity, and response time. Many of these parameters can be explicitly expressed as a function of light current. For a photo-conductive device, the photocurrent could be given by $I_{\rm ph}=q\phi\eta_\alpha g$, where ϕ is the incident number of photons per second, and $\eta_\alpha=(1-{\rm e}^{-2\alpha l})/2$ is the absorption quantum efficiency, where α is the absorption coefficient corresponding to the material structure and property, and l is the length of active region. The photoconductive gain is defined by $g=\tau_{\rm mc}/\tau_{\rm T}$[22] and the transit time for the carriers to cross the detector active region is $\tau_{\rm T}=l/\mu E$, where E is the electric field. Apparently in the light current the quantum efficiency represents the photo-generation process and photocarrier gain represents the transportation process. One point that should be noted is that the optical absorption is proportional to carrier density ($\Delta N/N_0=\Delta\alpha/\alpha_0$, where ΔN and $\Delta\alpha$ are the variations of the carrier concentration and absorption coefficient after irradiation, α_0 is the absorption coefficient

pre-irradiation).[23] The displacement damage effect on absorption quantum efficiency only plays a minor role in the light current when the irradiation fluence is relatively low. Hence, the photocurrent can be described as $I_{\rm ph} \propto \tau_{\rm mc}\mu$, which considers the minority carrier lifetime and mobility that are the decisive parameters with respect to the displacement damage effect on the light current.

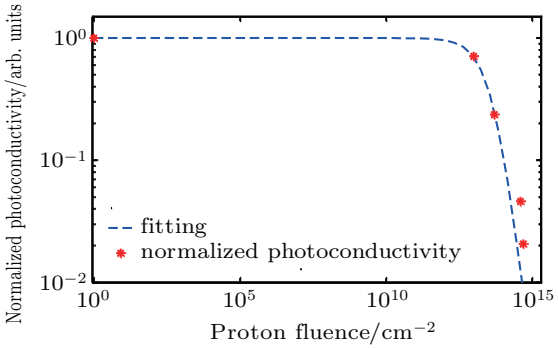


Fig. 4. (color online) Normalized photoconductivity of NWs photo-detector is plotted versus irradiation proton (1 MeV) fluence, the dashed line is according to the fitting formula and $*$ is the measured data which is extracted from light current I–V curve at -0.5 V. (Goodness of fit: SSE ~ 0.001706, R-square ~ 0.9977).

The effect of displacement damage on carrier mobility is also considered as an important factor, particularly in opto-electronic device operation. The carrier mobility is expressed as $1/\mu \approx 1/\mu_0 + K_\mu \varphi$,[24] where μ and μ_0 are the post-irradiation and pre-irradiation mobility, respectively. K_μ is the majority carrier mobility damage coefficient. In terms of carrier lifetime, the corresponding damage coefficient K_τ is usually defined as $1/\tau(\varphi) = 1/\tau_0 + K_\tau \varphi$ with $\tau(\varphi)$ and τ_0 being the post- and pre-irradiation lifetime, respectively.[24] Originally the minority carrier lifetime of NWs of pre-irradiation is $\tau_0 \approx 0.32 \times 10^{-9}$ s, and the carrier mobility is $\mu \approx 1.0 \times 10^3$ cm^2·V^{-1}·s^{-1}.[21] Taking into consideration both minority carrier lifetime $\tau(\varphi)$ degradation and carrier mobility $\mu(\varphi)$ damage, the normalized photoconductivity can be plotted and fitted in Fig. 4, with fitted parameters $K_\tau \approx 6.20 \times 10^{-5}$ cm^2·s, and $K_\mu \approx 1.99 \times 10^{-17}$ V·s. It should be pointed out that in the light conditions, the carrier mobility damage coefficient is approximate to the one in the dark conditions,[21] which infers that the damage coefficient of carrier mobility is stable under the irradiation of photons. The fluence-dependent $\tau(\varphi)$ and $\mu(\varphi)$ are shown in Figs. 5(a) and 5(b), respectively. The tendencies of decrease in both minority carrier lifetime and carrier (electron) mobility look similar and are consistent with that of the degradation of light current.

Remarkable decline in the photoconductivity of the device, when $\varphi > 1.0 \times 10^{12}$ cm^{-2}, is mainly due to both carrier lifetime and mobility decreasing. On the other hand, in terms of the band-to-band photoconductivity, the change in carrier concentration derived from photo-excitation is influenced by irradiation damage that is different from the scenario of the dark current. The degradation of photocurrent indicates that the proton radiation induced point defects cause both the minority carrier lifetime and carrier mobility to decrease synchronously. In addition, it provides a new approach to investigating the minority carrier lifetime and the point defect behavior in the nanowire. Comparing with the 2-μm-thick GaAs heterostructure of GaAs film with a carrier lifetime damage coefficient of $\sim 7.93 \times 10^{-3}$ cm^2·s under irradiation of 1.2-MeV protons (two orders higher than NWs), GaAs film has radiation resistance less than GaAs NWs in resisting proton irradiation.[25] Although all the parameters that are affected by the irradiation are measured independently, as long as the dark conductivity and photoconductivity are concerned, more specific experimental data to discriminate those factors are required to clarify the whole mechanism needed to be performed. Future work is expected to focus on a single NW device to gain a more specific understanding of each parameter independently.

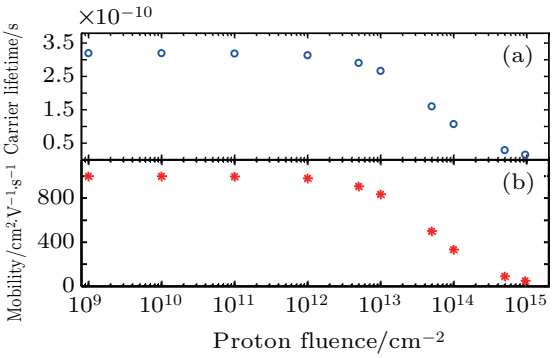


Fig. 5. (color online) Plots of (a) carrier lifetime and (b) carrier mobility degradation versus proton irradiation fluence, showing that both parameters in this photo-detector decrease with fluence in a similar manner.

It is well known that the quantum well (QW) is another important nanostructure. So far, in terms of GaAs, the quantum well infrared photo-detector (QWIP) is the only nano-device that has been studied in the ion irradiation effect.[26] Comparing the radiation tolerance of the NW photo-detectors (NWPDs) with that of QWIPs, the variations of operability of the devices with irradiation fluence are shown in Fig. 6. The operability of the device is defined by photoconductivity/responsivity reduction (e.g., if the photocurrent at a specific voltage is reduced by a factor of 10, the operability is 0.1). Generally the QWIP is grown by molecular beam epitaxy, and it has a 0.8-μm-thick bottom contact layer GaAs, a 32-repeat multiple QW structure with 36-nm wide AlGaAs barriers and 7.5-nm wide GaAs wells, a 0.4-μm-thick GaAs top contact layer, and the device is irradiated from the top in a vacuum at room temperature, therefore the energetic protons will penetrate to a depth of 2.6 μm totally from the top contact layer to the bottom. It has been known that in an energy range from keV to MeV, protons with lower energy will create more damage in GaAs due to the nuclear interaction.

Therefore, the plot of QWIP operability versus fluence under 1-MeV proton irradiation should be located between the curves of 0.8 MeV and 3 MeV. While the curve of degradation of the NW photo-detector is plotted between the curves of 3 MeV and 10 MeV, which suggests that the NW optoelectronic device performance reduces less than its QW counterpart in resisting proton irradiation.

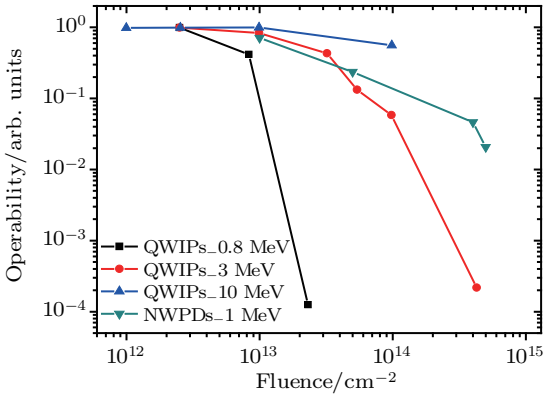


Fig. 6. (color online) Plots of photo-detector operability versus proton fluence for both QWIPs and NWPDs. Data for QWIPs are cited from Ref. [26].

4. Conclusions

In this work, we characterize the GaAs/AlGaAs NW photo-conductive detectors irradiated by different fluences of protons. The irradiation induced damage mainly causes the optoelectronic performance to degrade for NW detectors. The result indicates that both of the carrier lifetime degradation and carrier mobility reduction are the main factors that cause the operability of the device to decrease. The comparison of operability between devices also indicates that GaAs NWs likely show better radiation tolerance than GaAs QWs in resisting proton irradiation.

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References

[1] Kato T, Susawa H, Hirotani M, Saka T, Ohashi Y, Shichi E and Shibata S 1991 *J. Cryst. Growth* **107** 832
[2] Stettner T, Zimmermann P, Loitsch B, Doblinger M, Regler A, Mayer B, Winnerl J, Matich S, Riedl H, Kaniber M, Abstreiter G, Koblmuller G and Finley J J 2016 *Appl. Phys. Lett.* **108** 5
[3] Wei W, Liu Y G, Zhang X, Wang Z and Ren X M 2014 *Appl. Phys. Lett.* **104** 4
[4] Badada B H, Shi T, Jackson H E, Smith L M, Zheng C L, Etheridge J, Gao Q, Tan H H and Jagadish C 2015 *Nano Lett.* **15** 7847
[5] Aberg I, Vescovi G, Asoli D, Naseem U, Gilboy J P, Sundvall C, Dahlgren A, Svensson K E, Anttu N, Bjork M T and Samuelson L 2016 *IEEE J. Photovolt.* **6** 185
[6] Seyedi M A, Yao M, O'Brien J, Wang S Y and Dapkus P D 2013 *Appl. Phys. Lett.* **103** 4
[7] Seyedi M A, Yao M, O'Brien J, Wang S Y and Dapkus P D 2014 *Appl. Phys. Lett.* **105** 3
[8] Yamaguchi M 2001 *Solar Energy Mater. Solar Cells* **68** 31
[9] Mitchell B, Trupke T, Weber J W and Nyhus J 2011 *J. Appl. Phys.* **109** 12
[10] Marcinkevicius S, Leon R, Cechavicius B, Siegert J, Lobo C, Magness B and Taylor W 2002 *Physica B* **314** 203
[11] Ma L Y, Li Y D, Guo Q, Ai E K, Wang H J, Wang B and Zeng J Z 2015 *Acta Phys. Sin.* **64** 154217 (in Chinese)
[12] Zhou Y P, Li F J, Che C, Tan L Y, Ran Q W, Yu S Y and Ma J 2014 *Acta Phys. Sin.* **63** 148501 (in Chinese)
[13] Li F J, Tan L Y and Zhou Y P 2014 *Appl. Mech. Mater.* **556–562** 5163
[14] Andrievski R A 2014 *Uspekhi Fizicheskikh Nauk* **184** 1017
[15] Shen T 2008 *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **266** 921
[16] Tan H, Williams J, Jagadish C, Burke P and Gal M 1996 *Appl. Phys. Lett.* **68** 2401
[17] Tan H H and Jagadish C 1997 *Appl. Phys. Lett.* **71** 2680
[18] Fu L, Tan H H, Johnston M B, Gal M and Jagadish C 1999 *J. Appl. Phys.* **85** 6786
[19] Joyce H J, Parkinson P, Jiang N, Docherty C J, Gao Q, Tan H H, Jagadish C, Herz L M and Johnston M B 2014 *Nano Lett.* **14** 5989
[20] Jiang N, Gao Q, Parkinson P, Wong-Leung J, Mokkapati S, Breuer S, Tan H, Zheng C, Etheridge J and Jagadish C 2013 *Nano Lett.* **13** 5135
[21] Fajun Li, Ziyuan Li, Liying Tan, Yanping Zhou, Jing Ma, Lysevych Mykhaylo, Lan Fu, Hark Hoe Tan and Jagadish C 2017 *Nanotechnology* **28** 125702
[22] Levine B 1993 *J. Appl. Phys.* **74** R1
[23] Claeys C and Simoen E 2013 *Radiation effects in advanced semiconductor materials and devices* (New York: Springer Science & Business Media 33)
[24] Pease R L, Enlow E W, Dinger G L and Marshall P 1987 *IEEE Trans. Nucl. Sci.* **34** 1140
[25] Parenteau M, Carlone C, Morris D and Khanna S M 1997 *IEEE Trans. Nucl. Sci.* **44** 1849
[26] Khanna S, Liu H, Wilson P, Li L and Buchanan M 1996 *IEEE Trans. Nucl. Sci.* **43** 3012