Preparation of Mesa Structural Near-Infrared n-Type Nanocrystalline-$FeSi_2$/*p*-Type Si Heterojunction Photodiodes

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Abstract
Mesa structural n-type nanocrystalline (NC) $FeSi_2$/p-type Si heterojunctions prepared by photolithography were evaluated as near-infrared photodiodes at room temperature. The effects of this structure on the heterojunction photodiode performances were studied. Their junction capacitance density and leakage current density were evidently reduced as compared with those of the normal structural photodiodes. The near-infrared light detection performance was investigated using a 1.31μm laser at room temperature. The detectivity was estimated to be 1.5×10^8 cm $\sqrt{Hz}/W$ at a zero bias, which was clearly improved as compared with that of the normal structural photodiodes. This should be because interface states are reduced accompanied by the interface area reduction.

Keyword: Mesa Diode; Nanocrystalline $FeSi_2$; Sputtering, Heterojunction

1. Introduction

Recently, the majority of silicon-based optoelectronic devices operating at the wavelengths of optical fiber telecommunications ranging from 1.3 to 1.55 μm have received much attention owing to the low loss and low dispersion characteristics of silica-base optical fibers [1,2]. Light sources and detectors, which are compatible with silicon technologies and can operate in these wavelength ranges, are desired for the further development of current electronics [3]. Semiconducting nanocrystalline iron disilicide (NC-$FeSi_2$) comprising crystals with a diameter range of 3-5 nm is a novel promising candidate material to be integrated with silicon for near-infrared (NIR) photodiodes, owing to its desirable semiconducting properties [4,5]. NC-$FeSi_2$ possesses the semiconducting properties close to those of the orthorhombic phase β-$FeSi_2$ and amorphous iron disilicide [6,7]. It is an ecologically friendly material due to the nontoxicity of its component elements (Fe and Si) that are abundant in nature [8]. Specifically, it possesses indirect and direct optical band gabs of 0.78 and 0.85 eV, respectively, corresponding to the telecommunication wavelengths ranging from 1.3 to 1.55 μm [9], and absorption coefficients greather than 10^5 cm^{-1} at 1.2 eV [10]. Furthermore, NC-$FeSi_2$ thin films can be grown on any substrate material at room temperature [11]. These specifics make this material suitable for application to silicon-based optoelectronic devices such as infrared optoelectronics, photovoltaics, and light emitting diodes. Even though the application of β-$FeSi_2$ to photodiodes has already been reported [12,13], there have ever been only few reports on such application of NC-$FeSi_2$ up to date.

Previously, NC-$FeSi_2$ thin films deposited by pulse laser deposition (PLD) [4] and facing-target direct-current (FTDCS) [8] were structurally examined and their electrical properties were investigated. We have reported that NC-$FeSi_2$ thin films shows n-type conduction with residual carrier densities of ~10^{19} cm^{-3}, and the carrier density is reduced by hydrogenation. n-Type NC-$FeSi_2$/p-type Si heterojunctions were electrically studied and evaluated as photovoltaics [8] and near infrared photodiodes [14]. They showed a rectifying action similarly to conventional p-n heterojunctions. However, its action is accompanied by a large junction capacitance and large reverse leakage current. This leakage current might be attributed mainly to interface states at the junction interface. These interface states act as trap centers for photo-generated carriers and markedly degrade the light detection performance.

In this work, in order to reduce the parasitic capacitance and interface charge capacitance of diodes, mesa structural photodiodes were prepared. This is the first report on NC-$FeSi_2$-based mesa structural photodiodes, to our knowledge. We report the improvement of capacitance-voltage (C-V) and current-voltage (I-V) characteristics.

2. Materials and Methods

Mesa structural n-type nanocrystalline (NC) $FeSi_2$/p-type Si heterojunctions were fabricated by photolithography. To remove the native oxide layer on a Si substrate prior to the deposition, the Si substrate was initially immersed in a dilute hydrofluoric acid (HF) solution and then rinsed with deionized water. After that, a resist liquid (ZPN-1150-90) was immediately coated by spin coating for 30 seconds. After Pre bake on the hot plate at 90 ^oC for 90 seconds, the pattern was made by the irradiation of ultraviolet light through the photo-mask for 13 seconds. After post bake on the hot plate at 110 ^oC for 70 seconds, the developing was made for 60 seconds with a developer (NMD-W 2.38%) and then rinsed with deionized water for 60 seconds. After that, n-type NC-$FeSi_2$ film was deposited on the pattern by FTDCS at room temperature. It was immediately set in a FTDCS deposition chamber which was evacuated to a base pressure of 1×10^{-5} Pa. NC-$FeSi_2$ thin films with a thickness of 350 nm were deposited onto the pattern using $FeSi_2$ targets (purity: 4N) at room temperature. The sputtering deposition was made at a pressure of 1.33×10^{-1} Pa with introducing Ar and H_2 gas at flow rates of 15 and 10 sccm, respectively. Then, using a radio frequency magnetron sputtering technique, Al and Pd ohmic contacts were formed on the NC-$FeSi_2$ films and Si substrates, respectively. The photoresist was cleaned by stripping solution for 15 minutes. A schematic illustration of mesa structural n-type NC-$FeSi_2$/p-type Si heterojunction photodiodes is shown in Fig.1.

The C-V characteristics of photodiodes were measured at room temperature in the dark, using a precision LCR meter (Agilent, E4980A), and the I-V characteristics were measured at room temperature in the dark and under illumination with a 6 mW, 1.31μm laser.

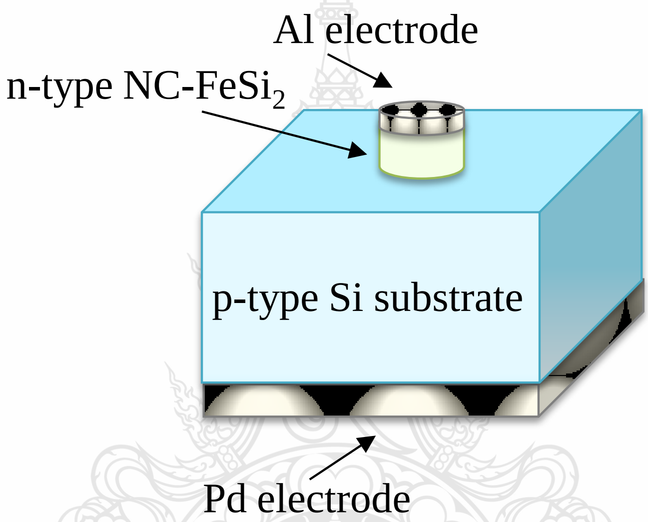

Fig. 1 Schematic diagram of mesa structural n-type NC-$FeSi_2$/p-type Si heterojunction photodiode.

3. Results and Discussion

Figure 2 displays the C-V characteristic curves of a mesa structural n-type NC-$FeSi_2$/p-type Si heterojunction, measured at a signal frequency of 500 kHz. For comparison, a normal structural n-type NC-$FeSi_2$/p-type Si heterojunction similarly fabricated by FTDCS was also measured. The junction capacitance density at a zero bias voltage of the mesa structural photodiode was 5.0 nF/cm^2, which is approximately 30% lower than that of the normal structural photodiode. This result indicated that the parasitic capacitance is reduced in the mesa diode.

Figure 3 shows a plot of $1/C^2$ against the applied bias voltage. The built-in potential of the mesa diode, which is estimated from the extrapolation of the$1/C^2$ curve approaching the bias voltage axis, is approximately 1 eV. This built-in potential value is in agreement with that of n-type β-$FeSi_2$/p-type Si heterojunctions [3]. Whereas the normal diode shows a nonlinear relation in the entire reverse bias voltage range, the mesa diode exhibits a linear slope in the reverse voltage range from -5 to -1 V. This result should be attributed to the reduction in the interface state of mesa diode, because the linearity of the slope is affected by the interface states at the junction interface. A nonlinear slope range from -1 to 0 V implies the existence of residual interface states [3,14].

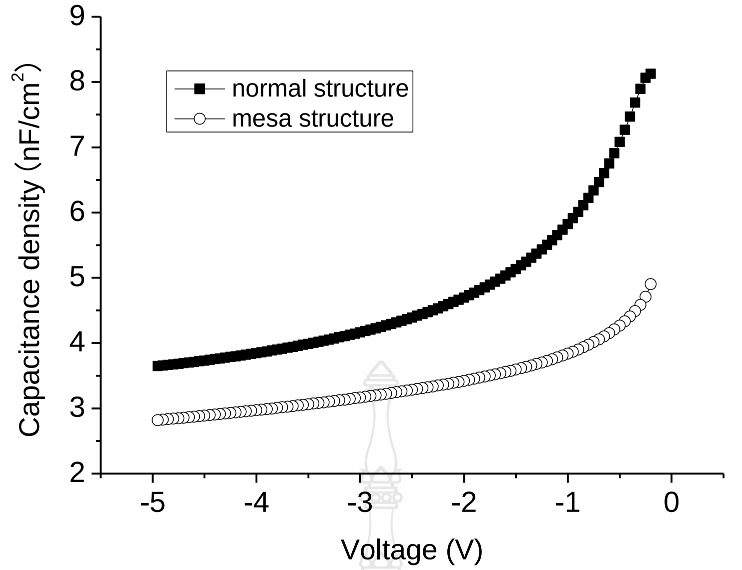

Fig. 2 C-V charecteristics of mesa and normal structural n-type NC-$FeSi_2$/p-type Si heterojunctions, measured at signal frequency of 500 kHz.

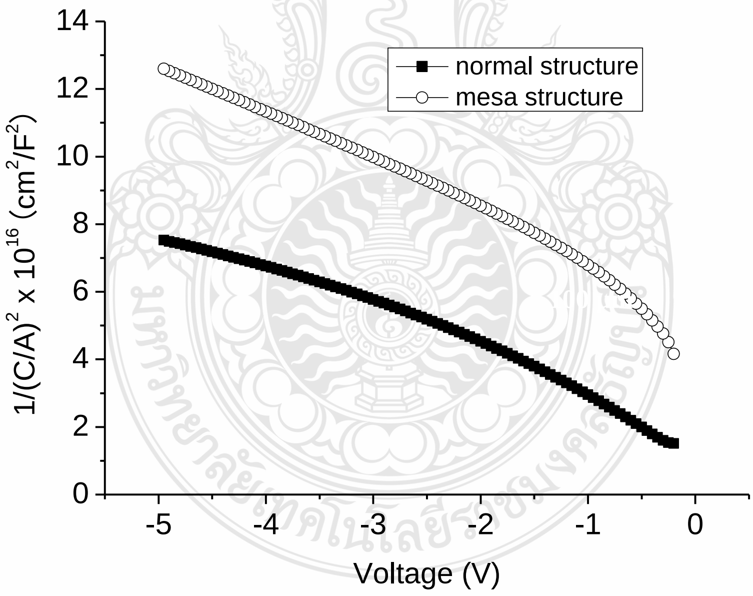

Fig. 3 The plots of $1/C^2$ against bias voltage of mesa and normal structural n-type NC-$FeSi_2$/p-type Si heterojunctions.

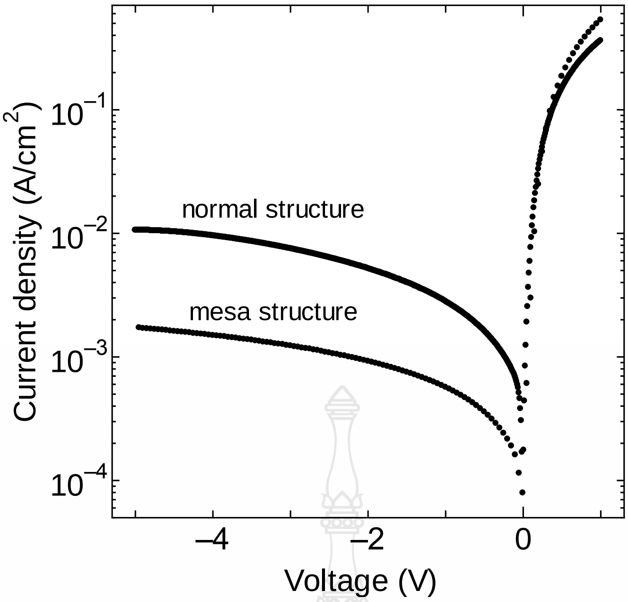

Fig. 4 J-V characteristics, which were measured in the dark at room temperature, of mesa structural and normal structural n-type NC-$FeSi_2$/p-type Si heterojunctions.

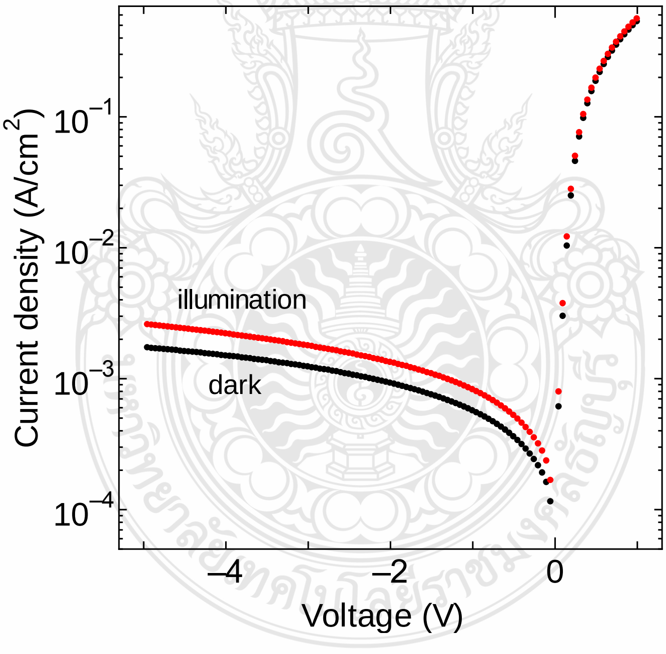

Fig. 5 Dark and illuminated J-V characteristics of mesa structural n-type NC-$FeSi_2$/p-type Si heterojunctions measured at room temperature.

Figure 4 displays the J-V characteristics of the normal and mesa diodes in the dark at room temperature. The mesa diode exhibits a good rectifying action with a rectification ratio of approximately three orders of magnitude at bias voltages of ±1 V, which is evidently improved as compared with that of the normal diode. Moreover, the leakage current of the mesa diode is clearly suppressed. This should be owing to the suppression in the interface state of mesa diode.

Figure 5 shows the J-V characteristic of the mesa diode measured in the dark and under illumination with a 1.31-μm, 6-mW laser. There was a small difference in the current between in the dark and under illumination. The photocurrent at a zero bias is 73.8 μA, and this value corresponds to a responsivity of 14.9 mA/W and a quantum efficiency of 1.2%.

Figure 6 shows the detectivities of the normal and mesa diodes as functions of the reverse voltage at room temperature. The detectivity of the mesa diodes is obviously superior to that of the normal diode, and in particular it reaches 1.5×10^8 cm √Hz/W at a zero bias.

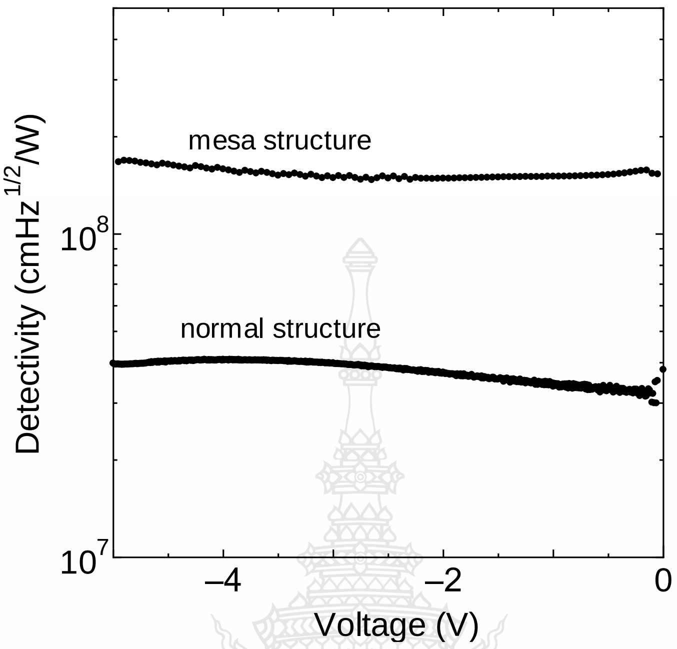

Fig. 6. Detectivity of mesa structural and normal structural n-type NC-$FeSi_2$/p-type Si heterojunction photodiodes plotted against bias voltage.

4. Conclusion

We fabricated the mesa structural n-type NC-$FeSi_2$/p-type Si heterojunction photodiodes by photolithography and experimentally demonstrated their NIR light detection performance at room temperature. Their junction capacitance density and interface state density were reduced as compared with those of the normal structural diodes. The devices showed good rectifying properties with a large rectification ratio. At zero bias, the quantum efficiency and detectivity were estimated to be 1.2% and 1.5×10^8 cm √Hz/W, respectively. These results show their ability to detect NIR light at room temperature and offer a high potential to employ them for practical application to NIR photodiodes.

References

[1] Suzuno M., Koizumi T. and Suemasu T., p-Si/β-FeSi2/n-Si double-heterostructure light-emitting diodes achieving 1.6 μm electroluminescence of 0.4 mW at room temperature, Applied Physics Letters, Vol. 94(21) p-213509, 2009.

[2] Shaban M., Nomoto K., Izumi S., and Yoshitake T., Characterization of near-infrared n-type β-FeSi2/p-type Si heterojunction photodiodes at room temperature, Applied Physics Letters, Vol. 94(22) p-222113, 2009.

[3] Shaban M., Izumi S., Nomoto K., and Yoshitake T., n-type β-FeSi2/intrinsic-Si/p-type Si heterojunction photodiodes for near-infrared light detection at room temperature, Applied Physics Letters, Vol. 95(16) p-162102, 2009.

[4] Yoshitake T., Yatabe M., Itakura M., Kuwano N., Tomokiyo Y., and Nagayama K., Semiconducting nanocrystalline iron disilicide thin films prepared by pulsed-laser ablation, Applied Physics Letters, Vol. 83(15), p-3057 2003.

[5] Li X. N., Li S. B., Nie L. F., Li H., Dong C. and Jiang X., Preparation of amorphous FexSi(1-x) film using unbalanced magnetron sputtering, Thin Solid Films, Vol. 518(24) p-7390, 2010.

[6] Milosavljevic M., Shao G., Lourenco M. A., Gwilliam R. M., Homewood K. P., Edwards S. P., Valizadeh R. and Colligon J. S., Transition from amorphous to crystalline beta phase in co-sputtered FeSi2 films as a function of temperature, Applied Physics Letters, Vol. 98(12) p-123506 2005.

[7] Milosavljevic M., Wong L., Lourenco M., Valizadeh R., Colligon J., Shao G. and Homewood K. P., Correlation of Structural and Optical Properties of Sputtered FeSi2 Thin Films, Japanese Journal Applied Physics Vol. 49, p-081401 2010.

[8] Shaban M., Kondo H., Nakashima K. and Yoshitake T., Electrical and Photovoltaic Properties of n-Type Nanocrystalline-FeSi2/p-Type Si Heterojunctions Prepared by Facing-Targets Direct-Current Sputtering at Room Temperature, Japanese Journal of Applied Physics, Vol. 47, p-5420 2008.

[9] Milosavljevic M., Shao G., Bilic N., Mckinty C. N., Jeynes C. and Homewood K. P., Amorphous-iron disilicide: A promising semiconductor, Applied Physics Letters, Volume 79(10), p-1438 2001.

[10] Takarabe K., Doi H., Mori Y., Fukui K., Shim Y., Yamamoto N., Yoshitake T. and Nagayama K., Optical properties of nanocrystalline FeSi2 and the effects of hydrogenation, Applied Physics Letters, Vol. 88(6), p-061911 2006.

[11] Milosavljevic M., Shao G., Gwilliam R. M., Gao Y., Lourenco M. A., Valizadeh R., Colligon J. S. and Homewood K. P., Semiconducting amorphous FeSi2 layers synthesized by co-sputter deposition, Thin Solid Films, Vol. 461(1), p-72 2004.

[12] Ootsuka T., Fudamoto Y., Osamura M., Suemasu T., Makita Y., Fukuzawa Y. and Nakayama Y., Photoresponse properties of Al/n-β-FeSi2 Schottky diodes using β-FeSi2 single crystals, Applied Physics Letters, Vol. 91, p-142114 2007.

[13] Promros N., Yamashita K., Izumi S., Iwasaki R., Shaban M. and Yoshitake T., Near-Infrared Photodetection of n-Type β-FeSi2/Intrinsic Si/p-Type Si Heterojunctions at Low Temperatures, Japanese Journal of Applied Physics Vol. 51, p-09MF02 2012.

[14] Promros N., yamashita K., Li C., kawai K., Shaban M., Okajima T. and yoshitake T., n-Type Nanocrystalline FeSi2/intrinsic Si/p-Type Si Heterojunction Photodiodes Fabricated by Facing-Target Direct-Current Sputtering, Japanese Journal of Applied Physics, Vol 51, p-021301 2012.