Investigation of Carrier Transient Response of Nanopatterned n-ZnO/a-Si(i)/p$^+$-Si Photodiodes

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***Abstract*—We investigated the carrier transient response of the nanopatterned silicon heterojunction photodiodes using ZnO as the n-type semiconductor. The results show that under the constant light illumination intensity, the planar structure has faster carrier response than the nanopatterned amorphous silicon (intrinsic) (a-Si(i)) diodes. It is attributed to a higher number of generated carriers in the nanostructure (due to the lower surface reflectivity) that increases the probability of collisions. On the other hand, the shortest response time of the device with nanopatterned p$^+$-Si suggests that carriers can be effectively transported vertically and horizontally through the p-i(intrinsic)-n structure. Furthermore, the wavelength-dependent rise time is correlated to the different transport distance between electrons and holes at different excited wavelengths.**

***Index Terms*—Heterojunction photodiodes, natural lithography, solar cells, transient response.**

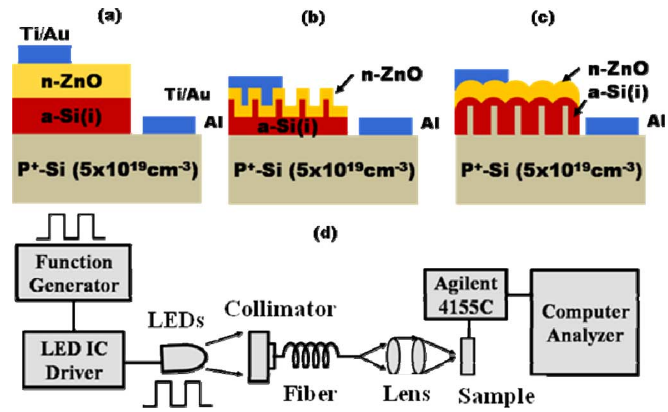

Fig. 1. Device structures of (a) planar n-ZnO/a-Si(i)/p$^+$-Si (Device A), (b) n-ZnO/nanopatterned a-Si(i)/p$^+$-Si (Device B) and (c) n-ZnO/a-Si(i)/nanopatterned p$^+$-Si (Device C). (d) Experimental setup of the transient response measurement.

I. Introduction

THE applications of nanostructures on photodetectors or solar cells have the advantages of reducing the surface reflectivity, improving the acceptance angle, and enlarging the absorption area [1]–[6]. Generally, effective reduction of surface reflectivity results in more photons captured in the layer structure [1], [3], [4], [6]. There are also reports of coating a monolayer of nanoparticles [7] or fabricating nanocones [8] on the device surfaces to increase light acceptance angles, which can improve solar energy utilization. Other issues such as the choice of light absorbing materials in the p-i-n structure and the carrier transport mechanism to complete electric conducting paths have significant impact on the photoresponse. For typical photodiodes or solar cells, high-quality materials and interfaces are required to reduce defects to ensure enough carrier lifetime for carriers to transit to the contact electrodes. Moreover, as the carrier mobility and lifetime are related to carrier density, the surface morphology-dependent light collection may have influence on the carrier transit time, which in turn affects the photoresponse.

The behaviors of transient response in a-Si : H(hydrogen) p-i-n diodes have been discussed in the literature [9]–[11]. The response time of a-Si : H p-i-n diodes is correlated with the incident light wavelength [9], [10] and is limited to the hole transport across the material structure [11]. Recently, the response behavior of n-ZnO/p-Si heterojunction diodes is reported for the application to ultraviolet (UV) detectors [12] with the transient response limited to the traps in ZnO material. They have the potential application for solar cells due to the property of wideband absorption [7]. To understand the influence of nanostructures on the carrier transit time, we investigate the transient photoresponse at different wavelengths on n-ZnO/a-Si(i)/p$^+$-Si heterojunction photodiodes. We fabricated nanopatterns on either the p-type Si substrate or on the a-Si(i) layer. The transient response was characterized under either a constant light illumination intensity or a constant photocurrent.

II. Device Fabrication

The transient response time was extracted from the photodiodes with nanopatterns on either the p$^+$-Si or the a-Si(i). We also prepared a planar device for comparisons. The layer structures of the planar n-ZnO/a-Si(i)/p$^+$-Si, n-ZnO/nanopatterned a-Si(i)/p$^+$-Si and n-ZnO/a-Si(i)/nanopatterned p$^+$-Si heterojunction photodiodes are sketched in Fig. 1(a)–(c) with the nomenclature Devices A, B, and C, respectively. For

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these samples, p^+-Si with a resistivity 1×10^{-3} Ω-cm was employed as the substrate. The 200-nm-thick a-Si(i) layer was first deposited on p^+-Si by plasma-enhanced chemical vapor deposition (PECVD). The nanopatterns were obtained by simply spin-coating a monolayer of silica nanoparticles with the diameter 100 ± 10 nm on the a-Si (Device B) or p^+-Si (Device C) surface as the etch mask and followed by reactive ion etching (RIE) with an etching depth 70 nm. The silica particles were then removed by dipping the samples in buffer oxide etching (BOE). The 200-nm-thick ZnO thin film doped with 3-wt% Ga was deposited by radio-frequency magnetron sputtering as the n-type semiconductor. The illumination mesa area is $200 \times 200\ \mu m^2$. The purpose of using a ZnO thin film as the n-type semiconductor is for easy fabrication as it can be coated by sputtering and the wide bandgap properties can be employed to absorb short wavelength optical intensity, which may be an advantage for solar cell applications [7]. Finally, Al (200 nm) and Ti–Au (12 nm/ 200 nm) were evaporated as the p-type and n-type contact electrodes, respectively.

III. Transient Responseof Photodiodes

The response time of the devices was measured using the setup shown in Fig. 1(d). The light source [light-emitting diodes (LEDs)] was driven by a pulsewidth-modulated (PWM) electrical controller that delivers an optical signal with the rise and fall time shorter than 50 ns. The wavelengths of the LEDs were chosen to be 633, 591, 516, and 458 nm, respectively, all with full-width at half-maximum (FWHM) bandwidth around 20 nm. The light source was fed into a fiber and collimated by two focal lenses to provide uniform illumination intensity on the samples. The photocurrents were extracted by the Agilent HP4155C semiconductor parameter analyzer under a 2-V reverse bias. In the following discussion, two experimental conditions, a constant illumination intensity and a constant photocurrent, were implemented. The rise and fall times of the samples are defined by the photocurrent increased from 0% to 90% and decreased from 100% to 10% of its maximum, respectively.

The transient response measurement was first performed under a constant $4.5 \times 10^7\ \mathrm{mW/cm^2}$ light intensity. The surface reflectivity of planar a-Si(i)/p^+-Si, nanopatterned a-Si(i)/planar p^+-Si and nanopatterned p^+-Si at the wavelength of 633 nm are 30.44%, 21.50%, and 22.09%, respectively. Fig. 2(a) shows that, at the wavelength 633 nm, the photocurrents of these samples vary to each other mainly due to the difference of surface reflectivity between the planar and nanopatterned structures. Other factor that results in the difference of photoresponse is related to the number of generated carriers that transport to the contact electrodes within the carrier lifetime. Comparisons of the rise and fall times between Devices A and B in Fig. 2(b) and (c) at different wavelengths suggest that the response time is increased with the number of generated carriers, as the probability of carrier collisions to each other becomes higher. On the other hand, despite the increase of electron and hole carriers in Device C (see the photocurrent in Fig. 2(a), which takes the wavelength 633 nm for example), the transient response of Device C is the fastest among the samples. Such an interesting phenomenon leads us to explore the transient response time of those samples by controlling the illuminated optical intensity to achieve the same photocurrent. The purpose of this measurement is to control the variations of surface reflectivity and semiconductor layer absorption so that the effect of nanostructure on the transient response can be studied.

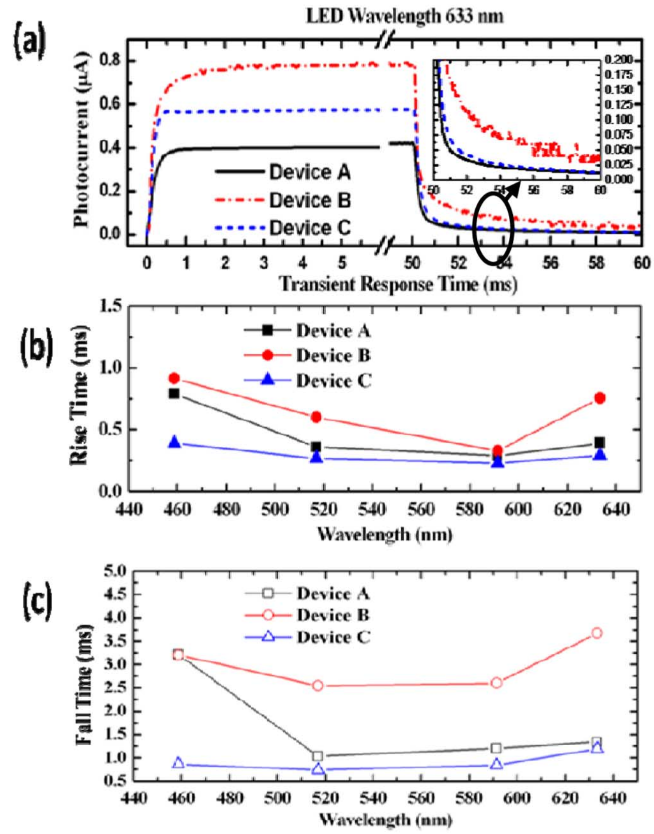

Fig. 2. (a) Transient photoresponse of the devices under a constant light illumination intensity at the wavelength 633 nm (inset: the close-up view of the dark currents). The corresponding rise (b) and fall (c) times are shown.

The response time under the constant photocurrent 750 nA is demonstrated in Fig. 3. Both the nanopatterned Device B and C have shorter rise and fall times than the planar structure. Moreover, the shortest response time of Device C suggests that both electrons and holes can be more effectively transported to the contact. As suggested in the inset of Fig. 4, the p-i-n structure is aligned not only vertically on the nanorod (or nanocone) tips but also horizontally along the rod sidewalls. Thus, the nanostructure can effectively shorten the carrier transit paths as both the electrons and holes can be swept to the nearby n- and p-type semiconductors horizontally or vertically at a shorter time. The roughening nanostructure creates more paths that carrier can be readily transported without crowding at the light absorption layer. It is in contrast to the case that the response time is increased with the number of carriers in the light absorbing region as suggested by comparing Devices A and B in Fig. 2.

Furthermore, from Fig. 3, we observe a dependence of the rise time on the wavelength. The rise time at 458 nm is the longest. We believe it is attributed to the location in the p-i-n structure where carriers are generated. At the wavelength 458 nm, light absorption mainly occurs in the ZnO/a-Si interface, which suggests that holes have to travel over the a-Si and p-Si layers to

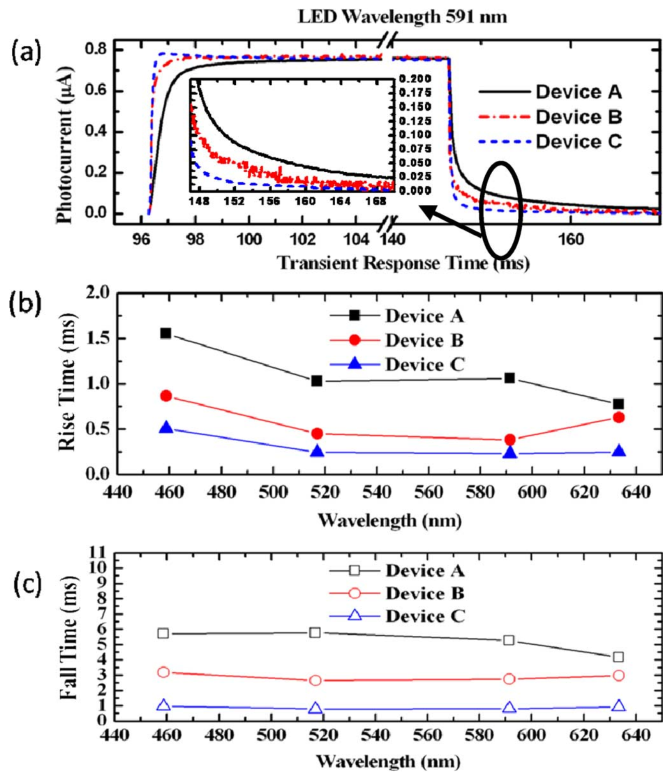

Fig. 3. (a) Transient photoresponse of the devices under a constant photocurrent at the wavelength 591 nm (inset: the close-up view of the dark currents). The corresponding rise (b) and fall (c) times are shown.

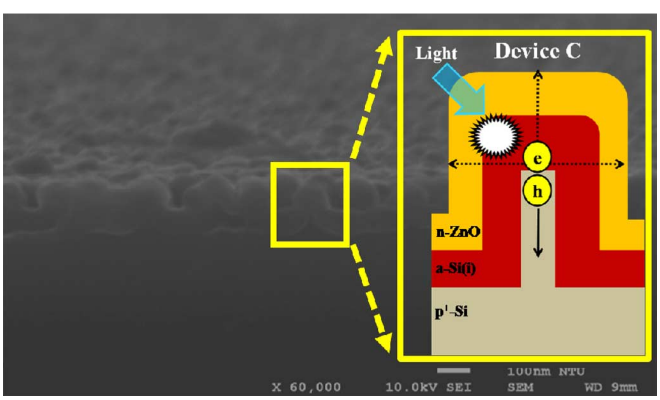

Fig. 4. Surface image of Device C indicates nanocone profiles of the p-i-n structure. (Inset: the schematic diagram of carrier transit paths.)

reach the negative electrode at the p-Si side. On the other hand, at 633 nm, carriers are mainly generated in the a-Si layer and the a-Si/p^+-Si interface, and electrons have to transit across the a-Si and ZnO layers to the n-type electrode. As the carrier mobility of holes (4×10^{-4} cm^2/Vs in a-Si [13]) is much smaller than that of electrons (0.1 cm^2/Vs in a-Si [13]), the rise time at the short wavelength is longer.

IV. Conclusion

Carrier response time of the n-ZnO/a-Si(i)/p^+-Si photodiodes with nanopatterns was explored under the condition of either a constant light illumination intensity or a constant photocurrent. In the former condition, Device B has slower response than that of the planar structure due to a larger amount of carriers crowded in the light absorbing region that increases the probability of collisions. And in the latter condition, the shortest response time of Device C suggests that carriers can be effectively transported vertically and horizontally through the p-i-n structure. We also observe that the rise time is dependent on the wavelength due to different transport distances for electrons and holes.

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