Materials Letters 176 (2016) 257–260

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

Power-dependent lateral photovoltaic effect in a-Si:H/c-Si *p-i-n* structure at different temperatures

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ARTICLE INFO

Article history:
Received 28 January 2016
Received in revised form
18 April 2016
Accepted 19 April 2016
Available online 20 April 2016

Keywords:
Amorphous silicon
Schottky barrier
Optical materials and properties
Photovoltaic effect
Optical detectors

ABSTRACT

In this letter, we report the power-dependent lateral photovoltaic effect (LPE) in a-Si:H/c-Si *p-i-n* structure at different temperatures for the first time. It was found that the position sensitivities of different temperatures all have the similar tendency, which increases gradually until become saturated with increasing laser power from 0.1 mW to 70 mW due to the competition between the increase number of generated electron-hole pairs and the increase of recombination probability. Moreover, the LPE of different laser powers all decreased considerably with decreasing temperature from 295 K to 80 K, and the saturated position sensitivity of 15.31 mV/mm at 295 K is about 21.26 times as large as that of 80 K, which can be ascribed to both the temperature-dependent Schottky barrier (SB) height and indium tin oxide (ITO) layer resistivity.

1. Introduction

The lateral photovoltaic effect (LPE), since it was first discovered by Schottky in 1930 [1] and later expanded by Wallmark in Ge p+-n junctions in 1957 [2], has attracted much attention due to its potential applications in position-sensitive detector (PSD) devices, shaft encoders, guidance system, optical alignment sensors and so on. The performance of a LPE-based device is usually evaluated on the basis of three parameters: position sensitivity, nonlinearity, and working area. Till now, researchers have tried many methods of modulating the LPE, such as searching for new material systems (semiconductor *p-n* heterostructure [3–5], metal-semiconductor or metal-oxide-semiconductor structure [6–8], perovskite materials [9,10], and organic semiconductor polymers [11]); microfabrication technology [12]; external modulation [13–15]; and side irradiation [16].

The hydrogenated amorphous silicon (a-Si:H), as one of the most promising wide band gap materials, has also attracted much attention for its excellent photoelectrical properties. More importantly, it can be deposited on many substrates over large areas homogeneously, such as monocrystal Si (c-Si), glass, metal, or even plastic, using the CMOS compatible low-temperature plasma-enhanced chemical vapor deposition technique, which makes it more suitable as photoelectric material, especially in hybrid photonic–electronic chips or devices [17,18]. Taking advantage of these properties of a-Si:H based devices, till now, the LPE of a-Si:H *p-i-n* structure has been reported by several groups [19–22]. However, these experiments were mainly conducted at room temperature. In fact, when a device is in use, it may work at different temperature environment, or even it stays at a constant temperature environment, the temperature of a device may also be changed due to long time working (Joule heat) or light illumination (photothermal) [13,23]. As is well known that the bandgap of a semiconductor is directly dependent on the working temperature, and the position sensitivity of a device should be different at different working temperatures due to the bandgap-dependent Schottky barrier (SB). However, to date, how the LPE depends on the temperature, and its related mechanism still remains unknown.

In this paper, for the first time we report the significant LPE in a-Si:H/c-Si *p-i-n* structure at different temperatures. Detailed studies on the power- and temperature-dependent LPE were presented. The position sensitivities of different temperatures all increased gradually until became saturated with increasing laser power due to the competition between the increase number of generated electron-hole pairs and the increase of recombination probability. Moreover, an obvious reduction of LPE with decreasing temperature was found experimentally, which can be successfully explained by the reduction of both the SB height and the

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http://dx.doi.org/10.1016/j.matlet.2016.04.149
0167-577X/

conductive layer resistivity.

2. Experimental methods and results

The a-Si:H film in this work was deposited onto *n*-type c-Si (100) substrate by plasma enhanced chemical vapor deposition (PECVD). The thickness of the wafer was 0.5 mm and the resistivity was about 4 Ω-cm at room temperature. The hydrogenated intrinsic amorphous silicon (a-Si:H(*i*)) layer was deposited on the first layer with thickness of 9 nm at about 473 K; then, a *p*-type doping hydrogenated amorphous silicon (a-Si:H(*p*)) layer was deposited on the front layer with thickness of 5 nm; at last, a 80 nm indium tin oxide (ITO) conductive layer was deposited by RF sputtering for 10 min at 423 K on the front surface. Details of the preparation can be found in Ref. [14].

The a-Si:H/c-Si *p-i-n* structure film was scanned spatially with a laser of 532 nm focused on a roughly 50 μm radius spot at the surface. All the contacts to the top and bottom surface were formed by alloying indium, and the transverse current-voltage (I-V) measurements suggest that this structure can produce a uniform SB [24].

Firstly, we measured the LPE of this a-Si:H/c-Si *p-i-n* structure film at room temperature, which was fixed on the cryostat with a quartz window. Fig. 1(a) shows the lateral photovoltage (LPV) as a function of laser spot position for the a-Si:H/c-Si *p-i-n* structure with a half contact distance (L) of 4.4 mm and under illumination of different laser powers, which was changed from 0.1 mW to 70 mW through an optical attenuation. Although the nonlinearity shows a particularly notable increasement as compared with that without a quartz window (especially for large laser power), as shown in Fig. 1(b), which may be due to some stray light reaching the film by means of window reflection and refraction, the largest nonlinearity of 7.53% is still much lower than the permitted limit of 15% [25]. Moreover, the position sensitivity as a function of laser power is also shown in Fig. 1(b). We can clearly observe that the position sensitivity increases from 0.19 mV/mm to a saturated value of 15.31 mV/mm with a threshold power of about 60 mW, the phenomenon of which is very similar with the previous studies [26,27].

Then, the power-dependent LPE of the a-Si:H/c-Si *p-i-n* structure film was studied under different temperatures ranging from 295 K to 80 K. The laser power-dependent position sensitivities for different temperatures are shown in Fig. 2(a). It is clear that the position sensitivities for other low temperatures have the similar tendency as that of 295 K, which increase quickly, and then increase gradually slow until saturate but with a lower saturated power. When the laser power increases, the number of generated electron-hole pairs increases quickly. However, the increased carriers have more probability to collide with each other during transition and free diffusion, which will result in the increase of recombination probability. Therefore, the position sensitivity will increase and tend to a saturated value at the end due to the competition between the increase number of generated electron-hole pairs and the increase of recombination probability. Fig. 2(b) shows the temperature-dependent position sensitivities for several typical laser powers. The position sensitivity depends strongly on the measurement temperature, and exhibits a clear nonlinear behavior, which decreases considerably with decreasing temperature from 295 K to about 200 K and then very slowly from 200 K to 80 K in the whole laser power range.

3. Discussion

In order to better understand the temperature-dependent LPE and explain the different decreasing ratio of position sensitivity on temperature behind this a-Si:H/c-Si *p-i-n* structure, we proposed the following model.

The optical absorption coefficient (α) of c-Si is approximately 1.11×10^6/m for 532 nm, so that the transmitted depth (d) is about 900 nm. Due to the high transmittance of ITO film and very thin a-Si:H layer, when the laser illuminates the surface, the photon energy was mainly absorbed in Si substrate to generate electron-hole pairs. According to the carrier's transmission and diffusion theory, LPV can be described as [7]:

$$LPV = K\left(N_A - N_B\right) = \frac{2K\delta n}{l_0} exp\left(-\frac{L}{l_0}\right)x \quad (-L < x < L) \tag{1}$$

where $n = \frac{P\lambda}{hc}$ is the number of electron-hole pairs generated per-second, K is a proportionality coefficient, l_0 is the diffusion length, δ is the probability for holes to be transmitted into the p-type layer, P is the laser power, λ is the laser wavelength, h is the Planck constant, and c is the speed of light. From Eq. (1), the involved position sensitivity of LPV can be presented as:

$$Sensitivity = \frac{2K\delta n}{l_0}\exp\left(-\frac{L}{l_0}\right) \tag{2}$$

Under the driving force of the built-in electric field of this structure, a part of generated holes will transmit to *p*-type layer, and although the number of the generated electron-hole pairs is very large, the number of the transmitted holes is very limited as to the very large transmission time and small recombination time

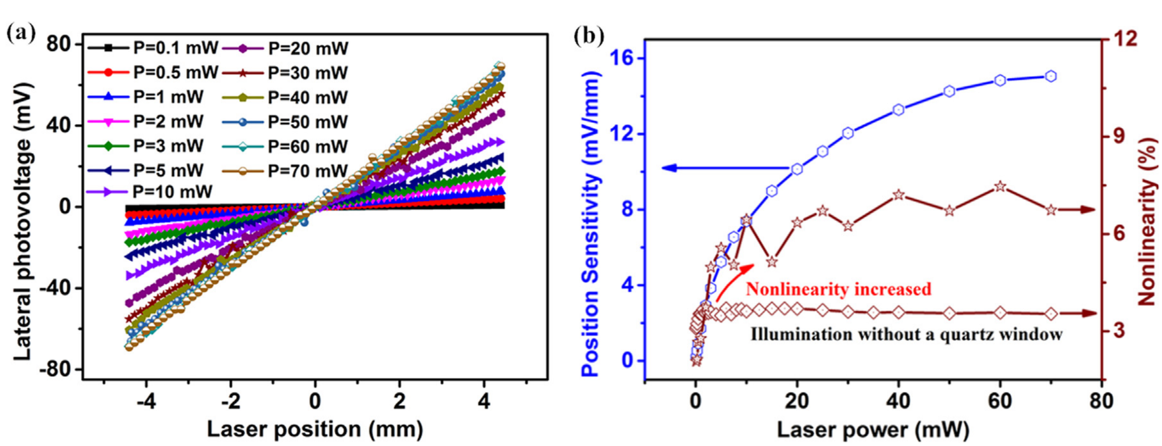

Fig. 1. (a) The LPVs as a function of laser position under illumination of different laser powers at room temperature. (b) The power-dependent position sensitivity and nonlinearity under illumination of a 532 nm laser.