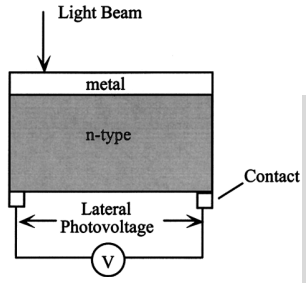
ADVANCED MATERIALS

Thin-Film Amorphous Silicon Position-Sensitive Detectors

By *Jasmine Henry** and *John Livingstone*



Optical position-sensitive detectors are a useful class of sensor with a wide range of applications in machine control systems, industrial alignment and robotic vision. They have distinct advantages over most arrayed discrete optical devices in that they can produce continuous optical signals, and versions based on thin-film amorphous silicon are not restricted by crystal growth limits and so have the potential to be fabricated in large area format. Sputter-deposited hydrogenated a-Si also has features such as excellent adhesion to glass substrates, precise film thickness, and hydrogen content control, which are of some interest in device design and fabrication.

1. Introduction

Position-sensitive detectors, or PSDs, comprise an important class of optical sensor, producing an electrical output, either voltage or current, which utilizes the lateral photovoltaic effect to give a linear relation between the output and the location of a spot of light impinging on a semiconductor surface. This phenomenon was first described by Schottky in 1930[1] and rediscovered by Wallmark in 1957.[2]

PSDs are used for a variety of optical applications, such as machine tool alignment, medical instrumentation, remote optical alignment, robotic vision, and other applications requiring precision measurements. Other interesting applications include telephone information systems,[3] surface profiling, angle measurement, rotation monitoring, guidance systems, and roles where precise automated control is necessary. PSDs are different to photodiode and other device arrays, e.g., those formed using charge coupled devices (CCDs), in that they can provide continuous information with no internal discontinuities.[4] The other advantages of PSDs over CCDs are that PSDs have better sampling frequencies (10 MHz to 10 kHz compared to 2 kHz) and they are cheaper. CCDs have the advantage that they are more effective at eliminating the effects of stray light.[5]

The wavelength sensitivity of these devices is, like all semiconductor optical devices, dependent upon the optical energy gap of the absorbing material so that a typical silicon-based single-crystal device has a maximum response in the region of 1000 nm. Our a-Si devices appear to have an optimal response to white light (peak wavelength 690 nm), which corresponds to an effective energy gap in the region of 1.8 eV. Light intensity does not appear to affect the linearity of device output, however, the magnitude of the response is directly related to the input power while operating below optical saturation. The devices, however, appear to lose linearity close to the contacts and this is attributed to edge effects related to electric field distributions.[4]

Typical light saturation for silicon-based PSDs is around 3 W/cm^2 and above this figure the photocurrent has a magnitude such that the voltage drop across the sheet resistance is so large that it equals reasonable values of reverse bias across the device in photodiode mode. At this point the p–n junction will be forward biased and hence the PSD no longer functions in this mode. Our devices have shown the best linearities in photovoltaic mode, with no advantage being gained in photodiode mode implying that we are approaching saturation with some of our optical sources. In a photodiode, saturation means that the production of photocurrent is saturated and can no longer increase with increasing light intensity. This leads to an accumulation of charge in the diode which slows it down. To remove these charges after the light is turned off, a recovery time is required.[5]

2. Mechanisms of Position-Sensitive Detector Operation

The simplest model of a PSD is that of a crystal-based device with a highly conducting top layer on a lower conductivity substrate, with appropriately placed contacts. They can

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detect position in either a one-dimensional or a two-dimensional sense.[2] When light is shone onto any p–n junction, electron–hole pairs are generated on both sides of the junction and carriers move down the potential gradient, with minority electrons moving from the p-side to the n-side and minority holes moving from the n-side to the p-side. This sets up a forward bias and a transverse photovoltage is set up—this is the basic mechanism of a solar cell output voltage, when the whole receiver surface is illuminated with light. If now a spot of light is shone on a junction that has one layer that is much more conductive than the other, a lateral photovoltage is also set up and we can observe a voltage parallel to the plane of the junction. As before, electrons and holes are generated on both sides of the junction, and the minority carriers are swept across the junction. The photogenerated carriers are swept down the built-in potential to the highly conducting layer, and spread rapidly in this plane, forming an equipotential layer. These carriers from the equipotential layer then re-inject into the less conductive layer. In this low-conductivity layer, slow-moving excess carriers are still located in the region of the light spot. It is the tendency of these bunched carriers to recombine with the re-injected carriers that constitute the lateral photovoltage. This photovoltage is a measure of the location of the light beam. Furthermore, the linear behavior of the incremental change in the voltage with distance along the receiver surface indicates the sensitivity, or the usefulness of the sensor.[6] This is the photovoltaic mode and Figure 1 shows a simplified crystalline example of a PSD in this mode. If however, the device is reverse biased, re-injection is inhibited by the increased

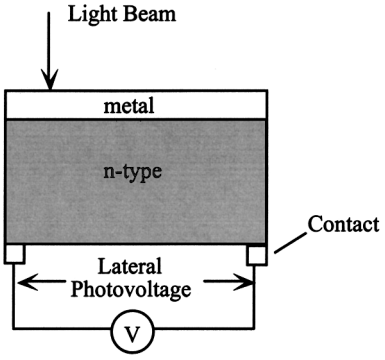

Fig. 1. A crystalline PSD configured for measurement in photovoltaic mode.

potential barrier, recombination is reduced, and the same contacts can be used to collect currents flowing in the base layer. In this case, current can be used to measure the location of the beam. This is the photodiode mode.

Amorphous silicon devices, such as those based on p–i–n and similar structures, follow the same general principles but the precise carrier flow mechanisms are more complex. As with p–i–n solar cells, electron–hole pair generation occurs in the intrinsic layer and carriers are then separated by the junction potentials so that electrons move to the n-layer and holes to the p-layer. These p–i–n structures can be configured as one- or two-dimensional devices and are widely researched. Mechanisms and properties of these devices are extensively discussed in the literature.[4,7–10]

Our work is focused on the optimization of the actual thin-film PSD structure so that we have concentrated mainly on one-dimensional devices with some two-dimensional devices constructed. We have designed a novel configuration comprising an indium tin oxide (ITO) layer, followed by an a-Si film and a platinum layer, and a typical configuration, which forms a Schottky barrier device, is shown in Figure 2.

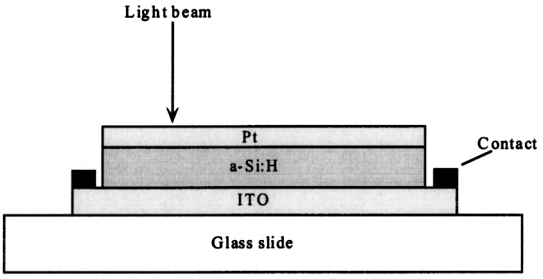

Fig. 2. A typical thin-film Schottky barrier device structure.

3. a-Si-based Position-Sensitive Detectors

PSDs based on crystalline structure have been widely reported[11] but major drawbacks of these devices are their limited area and high relative costs. These comparatively small devices require complex and expensive optical systems to ensure maximum utilization of their areas and to minimize inherent discontinuities.[3] Research devices are often made with pathlengths in the region of 20 mm, while commercial devices range from 2.5 mm to about 30 mm. Our devices, both crystalline and amorphous silicon, range from 16 mm to 20 mm by 10 mm.

Thin-film amorphous silicon is a well-established technology ■material?■ used extensively for the fabrication of solar cells.[12,13] In a position-sensitive detector it can be deposited as a transparent film, which makes it possible to utilize it for angular detection.[9] It also has a number of inherent advantages, including low-temperature processing capabilities, high photosensitivity and short detector response times of μs.[10] Its main drawback is the high defect state density, which can be greatly reduced using hydrogenation. Amorphous silicon can be prepared using many techniques, among the more common ones are radiofrequency (RF) and direct current (DC) glow discharge, RF sputtering, chemical vapor deposition (CVD), plasma-enhanced chemical vapor deposition (PECVD), and ion discharge. Most of the latest work is on a-Si:H PSDs fabricated using PECVD p–i–n structures.[4,10] These doped structures produce excellent linearity between voltage output and position. Of the plasma techniques, glow discharge and sputtering, the former has received the most attention probably due to its ability to produce films with superior optical and electrical properties[14] but reactive sputtering deposition has the advantage of permitting good control of the hydrogen content of the amorphous silicon.[15] Since the hydrogen content of a-Si:H has a major effect on the optical and electrical

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properties, this can be a useful tool for tailoring material properties to a particular use.

An important feature of a-Si, regardless of the deposition technique, is the presence of dangling bonds, which arise due to the non-periodic nature of amorphous silicon. In order to minimize the negative effects of these dangling bonds, hydrogen is incorporated in the film to compensate for these bonds, making the material suitable for electronic applications by reduction of the defect state density and the associated levels in the energy gap. The dangling bond density in non-hydrogenated a-Si is around 10^{19} cm^{-3} while in hydrogenated a-Si it is $<10^{17}$ cm^{-3}. Incorporation of hydrogen has a very large effect on key properties of the material, e.g., the effective energy gap can range from 1.61 to 1.88 eV as the hydrogen content varies from 7–21 at.-% and the resistivity can increase by some two orders of magnitude on moving from zero hydrogen to about 20 at.-% (in effect the material changes from a semimetal to a semiconductor). In addition to this, sputtered a-Si has excellent adhesion to the substrate and the films can be deposited for large-area devices limited only by target size and of course vacuum chamber size.[14]

4. Research Program

Our work involves the fabrication of thin-film amorphous silicon and crystalline devices, both of which show promising results. The thin-film silicon work is founded on a long research program studying the characteristics and properties of sputtered amorphous silicon, in particular its hydrogenation[15] and the light-induced Staebler–Wronski effect. Only the thin-film PSDs will be described here. Note that the sensitivities reported here are measured directly and are not amplified. Most of our devices are 20 mm × 10 mm.

Structure 1: ITO is dc sputtered onto glass followed by an RF deposition of a-Si:H for about 1 h, which produces films of approximately 0.5–1 μm thick. A Schottky barrier is then formed by evaporating Pt onto the a-Si:H layer. Finally two contacts are made to the Pt layer in the *x*-direction and two contacts to the ITO layer in the *y*-direction.

Structure 2: ITO is dc sputtered onto glass followed by the deposition of non-hydrogenated a-Si for 5–10 min, followed by a-Si:H for 1 h. A Schottky barrier is then formed as above with contacts in the *x*-direction and *y*-direction as in Structure 1.

Structure 3: Al contacts are evaporated onto glass, followed by 60 min of a-Si:H. A Schottky barrier is formed by evaporating Pt onto a-Si:H and finally, a second pair of contacts is made to the Pt film (*x*-direction), at right angles to the Al contacts (*y*-direction).

5. Results

All of the devices in this work showed optimal results in photovoltaic mode and only these results are reported here. Representative results from each structure are summarized in Table 1. This includes the sensitivity and nonlinearity measured for 500 μm increments under a red laser (5 mW) and focused white light (15 mW). Sensitivities for measurements along *x*- and *y*-directions were taken to assess the potential for future two-dimensional structures.

Table 1. Results for Structures 1, 2, and 3 tested under a red laser and focused white light with 500 μm increments. The *x* and *y* notation indicates measurements made along two directions at right angles on the PSD.

Structure		Red [μV/increment]	Red nonlinearity		White [μV/increment]	White nonlinearity	
1 (J2)	*x*	Poor	-	*x*	16	4.4%	$r = 0.998$
ITO/a-Si:H	*y*	Poor	-	*y*	12.9	5.9%	$r = 0.995$
2 (J25a)	*x*	9	4.5% $r = 0.999$	*x*	350	3.0%	$r = 0.999$
ITO/a-Si/a-Si:H	*y*	Poor	-	*y*	Poor	-	
3 (PSD 9)	*x*	1	24% $r = 0.990$	*x*	12	5.7%	$r = 0.998$
Al/a-Si:H	*y*	1110	Poor $r = 0.921$	*y*	2918	6.2%	$r = 0.992$

For an ideal device, when the voltage output versus distance moved is plotted, a linear relationship should be found. A figure of merit of a PSD is its nonlinearity, with a good device having nonlinearities less than 15 %.[4] This quantity is defined as follows:

$$\text{Nonlinearity} = \delta = 2s/F = \frac{2 \times \text{RMS deviation}}{\text{Measured full scale}} \quad (1)$$

and it is a measure of the distortion of the sensor output.

Another indication of device quality is the correlation coefficient, *r*, defined mathematically as

$$y - \bar{y} = r\frac{\sigma_y}{\sigma_x}(x - \bar{x}) \quad (2)$$

where σ is the standard deviation. The quantity *r* gives a good indication of device linearity with perfect linearity being indicated when *r* is ±1. Another important figure of merit is the spatial resolution of a device. This indicates the minimum distance that can be clearly measured when the light spot is moved from one position to another.

Structure 1: These devices have shown some good linear results and sensitivities of around 16 μV per increment with excellent linearities both in the *x*- and *y*-directions. An optimized two-dimensional structure is now being designed.

Structure 2: These devices have shown high outputs, an improvement on the Structure 1 devices, producing outputs of 350 μV per increment and excellent linearity. We believe that the non-hydrogenated a-Si acts like a semi-metal and makes an excellent contact between the a-Si:H and the ITO. A graph showing the response of this device under white light is shown in Figure 3.

Structure 3: Measurements were taken between the a-Si contacts and sensitivities of 2.9 mV per increment obtained, although with reduced linearity. Increased linearity was found across the Pt layer but with reduced sensitivities of 12 μV per increment.

The maximum spatial resolution is calculated by measuring the nonlinearities of devices for decreasing spatial increments

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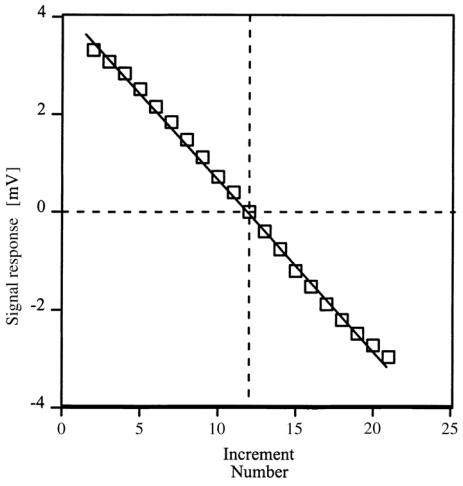

Fig. 3. Device J25a (Structure 2) tested under focused white light in photovoltaic mode resulting in a sensitivity of 350 μV per 500 μm increment.

and this gives an indication of the maximum spatial resolution, which is less than 50 μm in our best devices. These results are presented in Table 2.

Table 2. Calculated nonlinearities measured under focused white light for increments of 500 μm, 250 μm, 100 μm, and 50 μm.

Structure	500 μm	250 μm	100 μm	50 μm
1 (J2)	4.4%	6.4%	12%	20%
2 (J25a)	3.4%	3.5%	3.4%	2.3%
3 (PSD 9)	3.1%	3.6%	2.6%	-

6. Conclusions

In this work we produced three different PSD structures based on amorphous silicon, all of which showed promising results.

- Structures 1 and 2 appear to work as a pseudo n–i-SB (Schottky barrier) (■OK?■(structure with ITO acting as an n-layer, a-Si:H acting as the intrinsic layer and a Schottky barrier being formed with the Pt and a-Si:H. Improved contacts and the addition of resistive layers to the structures will improve device sensitivities. Structure 3 works as a straightforward Schottky barrier device.
- We tested all devices under red and white light. Even allowing for different optical intensities, devices performed better by a large margin in terms of linearity and sensitivity, under white light than with the red laser light. It is assumed that the optical response of a-Si:H to white light is greatly enhanced due to the energy gap of the absorbing region more closely matching that of the light source.
- Measurements taken along *x*- and *y*-directions were sufficiently promising to indicate that there is potential for useful two-dimensional PSDs.
- Nonlinearities of the devices were usually less than 5 % for increments down to 50 μm indicating useful devices for high-resolution applications.
- Future work will focus on the optimization of our devices to give linear results and high outputs in two dimensions. We will attempt to increase the size of our devices and the major challenges will be to maximize the active area while achieving high spatial resolution. Further attempts will be made to tailor material bandgaps to respond optimally to particular light sources.

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