A novel position-sensitive detector based on metal–oxide–semiconductor structures of Co–SiO$_2$–Si

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Abstract. Position-sensitive detectors (PSDs) founded on p–n junctions or metal–semiconductor (MS) junctions have been studied for many decades. This work reports a novel PSD based on Co–SiO$_2$–Si metal–oxide–semiconductor (MOS) structures. Different from the traditional MS devices where the results were mostly obtained at a given surface (semiconductor side), our MOS devices show better results for both the metal and semiconductor sides (the corresponding measurement methods are referred to as the obverse mode and the reverse mode). We systematically investigated the topographies of Co films, the transverse Schottky barrier (SB) $I–V$ characteristics, and the Co film thickness dependence of the position sensitivities measured in both modes. The maximum sensitivities, which occurred at 28 Å, are 42.64 and 51.98 mV mm$^{-1}$ for the obverse and reverse modes, respectively. The highest sensitivities measured in both modes are much larger than those of the classical MS devices and this can be attributed to the thin insulating SiO$_2$ layer between the Co film and the Si substrate. The position sensitivity measured in the obverse mode decreases greatly with increasing Co film thickness. We explain this by the shorting effect of the metallic film.

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1. Introduction

Position-sensitive detectors (PSDs) utilize the lateral photoeffect (LPE) to present a linear relation between the lateral photovoltage (LPV) output and the location of a laser beam incident on a given surface, which was first discovered by Schottky [1] and later expanded upon by Wallmark in 1957 [2]. The main area of application of PSDs is in precision optical alignment, such as biomedical applications, robotics, process control and position information systems [3]–[6]. Other attractive applications include surface profiling, rotation monitoring, telephone information systems [7], angle measurements [8], triangulation-based distance sensors [9, 10], guidance systems and roles where precise automated control is required. PSDs based on the LPE can provide continuous optical information over large areas with no internal discontinuities, which is the major advantage over arrayed discrete devices such as charge-coupled devices and photodiodes.

In judging whether a particular device works well, the two main criteria are the linearity of the LPV with light spot position and also the sensitivity (measured in mV mm\(^{-1}\)) of the device. Two well-developed devices of PSDs are Ti/Si amorphous superlattices deposited on Si substrates [11]–[14] and metal–semiconductor (MS) structures [15]–[18], both of which operate on the Schottky barrier (SB) mechanism in principle. However, the measurement mode is quite different: the LPV of the former device was measured by placing two ohmic contacts on the superlattice surface (hereafter we call it the obverse mode), while the latter was measured on the semiconductor surface (hereafter we call it the reverse mode). It is vital that the ohmic contacts should be placed on the resistive side (semiconductor) instead of the conductive side (metal) for MS devices since the conductive side easily gets shorted. Most interestingly, in this study we observed large position sensitivities and excellent linearities in Co films deposited on n-type Si substrates with a thin native SiO\(_2\) layer (1.2 nm) using both measurement modes (see figure 1). Such metal–oxide–semiconductor (MOS) structures have been extensively studied as solar cell materials for many decades [19]–[24], but so far little work on MOS performing as PSDs has ever been reported. Compared with the MS devices, our MOS devices not only exhibit larger position sensitivities but also manifest well for both measurement modes.

Our work is focused on the Co film thickness dependence of the position sensitivities for the MOS devices and is aimed at producing highly linear and sensitive PSDs using room temperature and readily reproducible fabrication techniques. The devices were tested under a He–Ne laser (3 mW and 632 nm). The thickness of Co films was varied between 16 and 480 Å and it was found that the optimal film thickness for both measurement modes is about 28 Å. The optimal position sensitivities for the obverse and reverse measurement modes are 42.64
Figure 1. Schematic illustration of the LPV measurement using a variable light spot position: (a) two fixing electrodes were placed on the Co film side (the obverse mode); (b) two fixing electrodes were placed on the Si side (the reverse mode).

and 51.98 mV mm$^{-1}$, respectively. We compare these two distinct measurement modes in detail and also present the topographies of Co films, the transverse SB $I-V$ characteristics and the effective resistivities of the Co films with changing thickness of the Co film.

2. Mechanisms of MOS PSD operation

It has been well established that the mechanism of such MOS solar cells with a native thin oxide layer less than 25 Å is similar to that of MS or SB solar cells [19, 21]. This oxide layer, although essentially transparent to electrons [25], allows a potential difference to exist between the metal and the semiconductor, resulting in an increased open-circuit voltage under illumination [21, 26]. Similarly, the operation mechanism of our MOS PSDs can also be attributed to the SB. When light is uniformly incident onto the MS (say n-type semiconductor) junction, electron–hole pairs are generated inside or within the minority-carrier diffusion length of the depletion region almost in the semiconductor. The minority holes in the depletion region are swept into the metallic film by the Schottky field with electrons remaining in the n-region. This leads to the development of a transverse photovoltage, as is observed in an MS or MOS solar cell. If now the light impinges at one point on the surface, the presence of the excess remaining electrons and injected holes will give rise to a non-equilibrium distribution because of all the other points on the film surface without any illumination, generating a gradient between the illuminated and the non-illuminated zones. So the excess holes in the metallic layer and the excess electrons (majority carriers) in the Si layer move laterally away from the illuminated spot. If the lateral distance of the laser spot from each electrode is different, then the quantity of the collected carriers at the two contacts is different. A lateral field is therefore set up, as well as the LPV. Ideally, there should be a linear relationship between the LPV output and the position of the light spot. This linear behaviour indicates the sensitivity, or the usefulness, of the sensor [27].

Figure 2 shows a simple energy-band diagram for our Co–SiO$_2$–Si MOS system. In MOS solar cells, the insulator energy bandgap ($E_{gi}$) is considered to be too high to lead to any light
Figure 2. Schematic simple equilibrium energy-band diagram of the Co–SiO$_2$–Si MOS system with an n-type semiconductor substrate. $E_{gi}$ and $E_{gs}$ denote the bandgaps of SiO$_2$ and Si, respectively. $\Phi_{mi}$ is the metal-to-insulator barrier height and is related to the work function of Co. $\Phi_{si}$ is the semiconductor-to-insulator barrier height and is related to the work function of Si. The semiconductor from the interface (Si/SiO$_2$) to bulk can be divided into three regions: the inversion layer, depletion region and neutral region as illustrated.

absorption and, providing the insulator (SiO$_2$) is kept thin enough (20 Å in silicon MOS cells), tunnelling through the insulator is the transport mechanism [21, 28, 29]. In our case, the native SiO$_2$ film is about 1.2 nm measured by transmission electron microscopy (TEM). According to the tunnel MOS theory [30, 31], the metal-to-insulator barrier height $\Phi_{mi}$ controls the degree of the inversion of the n-type base semiconductor. To invert the surface of an n-type semiconductor to p-type requires $\Phi_{mi}$ to be higher than an approximate value of 3.6 eV. Note that the work function (about 4.45 eV) of Co is much larger than the demarcation value, so the conductivity type of the semiconductor surface underneath the interfacial layer is inverted. Consequently, a pseudo p–n junction is formed and conversion of radiation to charge carriers occurs in the bulk of the base semiconductor. This may be the difference in photo-generated carrier mechanism between our MOS devices and the classical MS devices.

3. Experimental details

The Co thin films were deposited on n-type Si(1 1 1) at room temperature by dc magnetron reactive sputtering. The thickness of the wafers is around 0.3 mm and the resistivity of the wafers is in the range of 50–80 $\Omega$ cm at room temperature. Si substrates are covered with a thin native SiO$_2$ layer of 1.2 nm measured by TEM. The base pressure of the vacuum system prior to deposition was better than 5.0 \times 10^{-5} Pa. A high purity Co target (60 mm diameter) was used. An argon gas pressure of 0.64 Pa was maintained during deposition. The deposition rates, determined by a stylus profile meter on thick calibration samples, were 0.4 Å s$^{-1}$.

All samples were cut into 6 mm × 6 mm rectangles and were scanned spatially with a He–Ne laser (3 mW and 632 nm) focused on a roughly 50 µm diameter spot at the Co film.
surface and without any spurious illumination (e.g. background light) reaching the samples. This beam was chopped and the resulting photovoltage was measured using two distinct measurement modes shown in figure 1. All the contacts (less than 1 mm in diameter) to the films were formed by alloying indium and showed no measurable rectifying behaviour. The topography of the samples was measured using atomic force microscopy (AFM) in tapping mode. The transverse SB $I–V$ curves were measured with a current source (Keithley 2400). The Co film resistivity and lateral $I–V$ characteristic were determined using the current in the film plane (CIP) geometry four-terminal method by the physical property measurement system (PPMS; Quantum Design).

4. Results and discussions

Figure 3 shows the AFM images of the 16, 32, 64 and 120 Å thick samples. The average surface roughness of the 16, 32, 64 and 120 Å samples is 0.368, 0.424, 0.707 and 1.22 nm, respectively.

Figure 3. AFM images (1 × 1 $\mu$m$^2$) of Co films with different thicknesses deposited on SiO$_2$/Si substrates: (a) 1.6 nm, (b) 3.2 nm, (c) 6.4 nm and (d) 12 nm.

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Figure 4. The transverse SB $I-V$ curves of Co–SiO$_2$–Si MOS systems with different Co film thicknesses: 1.6, 3.2, 6.4 and 12 nm. The inset shows the schematic circuit of the sample measurement.

Obviously, both the average surface roughness and the grain size increase with the increment of Co film thickness. Furthermore, from the micrographs, we can see that all the films are continuous and approximately uniform. Since it is very important that the film is uniform in order to obtain high linearity [32], these roughly uniform films can guarantee good linearities of our MOS devices.

The typical transverse SB $I-V$ characteristics of Co–SiO$_2$–Si systems with different Co film thicknesses are shown in figure 4. One can see that all the $I-V$ curves exhibit good nonlinearities and rectifying current–voltage behaviour with the Co film thickness increasing from 1.6 to 12 nm, which is similar to that of the traditional MS devices. This demonstrates that all the MOS devices (Co film thickness varies from 1.6 to 48 nm) in this study can fully develop an SB. In comparison with the previous report about MOS solar cells [21, 33], however, our devices present a larger resistivity. This may be due to the large resistivity of the Si substrate (50–80 $\Omega$ cm), one order larger in magnitude than that (about 1–10 $\Omega$ cm) of the reported MOS solar cells. In addition, the current has a lot of scattering with Co thickness, presumably because of the sample differences, and possibly because of the measurement error. We indeed found that the $I-V$ characteristic measured after some time would behave slightly different from that measured instantly. This may be attributed to the heating effect of the circuit.

A representative response (Co$_{2.8}$ nm–SiO$_2$–Si device) of the induced LPV to the laser position at room temperature using both measurement modes is displayed in figure 5. For both modes, the LPV is largest when the incident radiation spot is closest to the measurement electrodes and shows a monotonic linear decrease as the spot is scanned away from the contacts, becoming null at the midpoint of these two contacts. Nevertheless, when the spot reaches past the contacts, the LPV of each mode decays to zero at different rates. The obverse mode is more remarkable than the reverse mode. This can be ascribed to the blocking of the optical excitation by alloyed indium dots which constitute the ohmic contacts at the same side as the incident laser for the obverse mode [34]. For the reverse mode, however, the ohmic contacts are on the
The obverse mode
The reverse mode

Figure 5. A representative plot (Co$_{2.8}$ nm–SiO$_2$–Si device) of the induced LPV as a function of the laser position at room temperature using both measurement modes. A, B, C and D correspond to the positions illustrated in figure 1.

opposite side of the incident laser; thus the response of the reverse mode reflects the position dependence of LPV with laser spot reaching past the contacts more effectively.

Since only the linear dependence of LPV between two ohmic contacts is useful for PSDs, we concentrate on the results obtained between two ohmic contacts for our MOS devices in the following discussion. According to Henry and Livingstone’s reports [15]–[18], there are two other figures of merit of a PSD apart from the position sensitivity. The first one is its nonlinearity, with an acceptable device having nonlinearities less than 15% [35]. This quantity, also known as position-detection error, is defined [35, 36] as follows:

\[
\text{Nonlinearity} = \delta = 2s/F = \frac{2 \times \text{rms deviation}}{\text{Measured full scale}}
\]

and it is a measure of the distortion of the sensor output. The second one is the correlation coefficient, \(r\), defined mathematically as

\[
y - \bar{y} = r \frac{\sigma_y}{\sigma_x} (x - \bar{x}),
\]

where \(\sigma\) is the standard deviation. The quantity \(r\) gives a good indication of device linearity with perfect linearity being indicated when \(r\) is \pm 1.

Results showing the difference in performance of our MOS devices with different Co film thicknesses using the reverse measurement mode are given in table 1. As with the classical MS (Al–Si, Ti–Si and Ta–Si) devices [17, 37], our MOS devices show improvement from the thick to thin metal films and produce an optimal position sensitivity at a certain film thickness (about 28 Å). However, the highest sensitivity (51.98 mV mm$^{-1}$) is much larger than that (10.62 mV mm$^{-1}$) of the reported MS devices. As discussed in section 2, these evidently increased sensitivities of our MOS devices over the traditional MS devices may be related to the insulating SiO$_2$ layer. Both the correlation coefficients and nonlinearities are all very good, whether for the thick or the thin films.
### Table 1. Results on Co–SiO$_2$–Si MOS devices using the reverse measurement mode with different Co film thicknesses.

| Position Co film thickness (Å) | Sensitivity (mV mm$^{-1}$) | Correlation coefficient, $r$ | Nonlinearity |
|-------------------------------|-----------------------------|-----------------------------|--------------|
| 0 No response                 | No response                 | No response                 | No response  |
| 16 42.82 0.999 5.9%           |                             |                             |              |
| 24 46.31 0.999 5.7%           |                             |                             |              |
| 28 51.98 0.999 6.1%           |                             |                             |              |
| 32 47.74 1 4.3%               |                             |                             |              |
| 48 38.10 1 4.9%               |                             |                             |              |
| 64 29.99 0.999 6.4%           |                             |                             |              |
| 120 20.15 0.999 7.4%          |                             |                             |              |
| 240 2.86 0.999 7.0%           |                             |                             |              |
| 480 1.34 0.999 6.8%           |                             |                             |              |

### Table 2. Results on Co–SiO$_2$–Si MOS devices using the obverse measurement mode with different Co film thicknesses.

| Position Co film thickness (Å) | Sensitivity (mV mm$^{-1}$) | Correlation coefficient, $r$ | Nonlinearity |
|-------------------------------|-----------------------------|-----------------------------|--------------|
| 0 No response                 | No response                 | No response                 | No response  |
| 16 4.08 1 5.0%                |                             |                             |              |
| 24 20.67 0.999 5.7%           |                             |                             |              |
| 28 42.64 1 4.2%               |                             |                             |              |
| 32 26.74 1 1.2%               |                             |                             |              |
| 48 10.73 1 5.2%               |                             |                             |              |
| 64 6.72 1 3.0%                |                             |                             |              |
| 120 2.70 1 3.1%               |                             |                             |              |
| 240 No response               | No response                 | No response                 | No response  |
| 480 No response               | No response                 | No response                 | No response  |

The most remarkable result in this work is that we also obtained good results for our MOS devices using the obverse mode. As shown in table 2 and figure 6(a), the devices were also reliably producing good sensitivities and linearities over a range of thicknesses, but the sensitivities were consistently lower than those measured in the reverse mode. The highest sensitivity achieved in this mode is 42.64 mV mm$^{-1}$. Interestingly, the optimal film thickness (about 2.8 nm) appears to be strikingly similar to that measured in the reverse mode.

Besides, the sensitivity reduces more rapidly to zero with increasing Co film thickness than that measured in the reverse mode. For example, the sensitivity for the Co$_{12}$ nm–SiO$_2$–Si device is only 2.70 mV mm$^{-1}$ while it is still as large as 20.15 mV mm$^{-1}$ in the reverse mode. We explain this by the shorting effect of the two ohmic contacts which establish the LPV measurement on the metal film side. The thicker the metallic film, the more remarkably the metallic film shorts...
Figure 6. (a) The position sensitivity in the obverse mode and effective resistivity as functions of the thickness of the Co film for Co–SiO$_2$–Si devices. (b) Lateral $I$–$V$ curves of Co$_{3.2}$nm–SiO$_2$–Si and Co$_{6.4}$nm–SiO$_2$–Si measured at 300 K. The inset in (a) shows the schematic measurement for both the effective resistivity and the lateral $I$–$V$ curves of MOS devices.

The two ohmic contacts, leading to a smaller LPV value. This can be further verified by the Co film thickness dependence of the effective resistivity for our MOS structures. The effective resistivities for our MOS devices measured in the Co film are also shown in figure 6(a). One can observe that with increasing thickness of the Co film from the peak point, the position sensitivity drops as dramatically as the effective resistivity does. In MOS structures, the effective resistivity measured on the metal film is strongly determined by whether the conducting channel switches from the upper metallic film to the Si inversion layer (this inversion layer is shown in figure 2) [38]–[43]. That is, the effective resistance is composed of two parallel channels. One is the metal film channel; the other is the Si inversion layer channel. The thicker the metallic film, the lower is its resistance compared to the constant inversion layer resistance, and therefore the metal film channel should play a major role in the effective resistivity, which leads to a smaller effective resistance and a more pronounced shorting effect.

Figure 6(b) shows the $I$–$V$ characteristics of Co films (3.2 and 6.4 nm) deposited on SiO$_2$/Si substrates measured at 300 K. The $I$–$V$ curve for Co$_{6.4}$nm–SiO$_2$–Si is representative of metallic behaviour, which suggests that the metal film channel should play a major role in the effective resistivity. For Co$_{3.2}$nm–SiO$_2$–Si, however, the $I$–$V$ curve is clearly nonlinear. At low currents, the sample exhibits low resistance, and at high currents it switches to the high resistance state. This implies that the effective resistance in Co$_{3.2}$nm–SiO$_2$–Si is determined by both the metal film channel and the Si inversion layer channel. This vivid contrast between these two $I$–$V$ curves further supports our interpretation for the Co-film-thickness dependence of position sensitivity measured in the obverse mode.

It is interesting to note that such MOS devices usually exhibit a large magnetoresistance (MR) effect in the obverse mode [38]–[43], namely that it is possible to integrate both LPE and MR effects into one structure like our Co–SiO$_2$–Si MOS devices. In practice, we have successfully achieved measurement of both these properties in the obverse mode in such MOS devices [44]. The consistent pace between the position sensitivity and effective resistivity

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(which can be affected by magnetic field) with increasing Co film thickness suggests a strong relationship between them. This may inspire us to predict that it is possible to realize magnetic field modulation of the LPE or PSDs and the light modulation of MR in such MOS devices, and we believe that this is the main or unique advantage of measuring in the obverse mode over measuring in the reverse mode. A further study on the relationship between the LPE and MR is under way.

5. Conclusions

In this work, we studied a novel PSD device based on Co–SiO$_2$–Si MOS structures using the obverse and reverse measurement modes, both of which showed promising results.

1. All the Co films of our MOS devices are continuous and approximately uniform and this promises to produce good linearities. Furthermore, all the MOS devices (the Co film thickness varied from 1.6 to 48 nm) can completely form an SB, which leads to the LPE when a given surface is non-uniformly illuminated.

2. We also measured the position dependence of LPV with the laser spot reaching past the ohmic contacts using the obverse and reverse modes. Due to the blocking effect of the indium contacts, the LPV measured in the former mode decays more rapidly to zero than that in the latter. Therefore, the response of the reverse mode reflects the position dependence of LPV with the laser spot reaching past the contacts more effectively.

3. The MOS devices exhibit good results for both measurement modes. The maximum sensitivities, which occurred at 28 Å, are 42.64 and 51.98 mV mm$^{-1}$ for the obverse and reverse modes, respectively. However, the sensitivity measured in the obverse mode is consistently lower than that in the reverse mode.

4. The position sensitivity measured in the obverse mode drops as dramatically as the effective resistivity does with increasing Co film thickness from the peak point. We explained this by the shorting effect of the Co film.

5. Future work will focus on the relationship between the LPE and MR. We will attempt to realize magnetic field modulation of the LPE or PSDs and light modulation of MR in such MOS devices.

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